Investigating the Impact of Co-located and Distributed Collaboration Using Multi-touch Tables

ALGHANIM, FIRAS,LOTFI

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Firas Lotfi Alghanim

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Abstract

With the intention to study the role of new interfaces in multi-user applications, multi-touch tabletops are investigated to examine if they effectively aid their users in working together synchronously. Multi-player games are selected as a case of collaborative work. Early studies of distributed multi-touch tabletops did not cover the HCI related aspects associated with multi-player games, especially in distributed configuration. The performance, collaboration, and usability aspects of HCI are studied in this research. A simple multi-player maze game has been designed and implemented over two connected and physically separated multi-touch tabletops. The aim of this work is to investigate the effects of distribution on players performance, collaboration, and usability of multi-player games over multi-touch tabletops, compared to playing in a co-located condition. Groups of participants have been randomly selected and assigned to play the game in pairs under two conditions: co-located where two players are playing the game on the same table, and distributed where they are playing the game but on separate tables. The collected data is statistically analysed to test for differences between the two conditions, as well as the differences of the strength of the correlation between the underlying factors. The results indicate that, in general, the differences are not significant for such type of applications if a simple and efficient communication mechanism is provided for the players in the distributed condition. Players expressed almost the same level of usability engagement and enjoyment for the two conditions. This may have a strong impact on the HCI aspects when designing such type of applications on the future.

This thesis is lovingly dedicated to my sons, Faisal and Khalid, who came into my life while I was doing this research.

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Declaration

No part of the material provided has previously been submitted by the author for a higher degree in Durham University or in any other university. All the work presented here is the sole work of the author and no one else.

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1 Introduction

"If you want to go fast, go alone. If you want to go far, go together." — African proverb

The topic of distribution of computer system's users has been widely studied by researchers in a variety of academic disciplines such as learning, information management, human-computer interaction, and computer supported collaborative work. Distribution of users means that a system's users are not in the same physical place, as oppose to being co-located, though they are using the same system at the same time. There are many software environments that support multi-users to work collaboratively together in co-located and distributed conditions. The majority of these software require the users to use the traditional interaction techniques of mouse-keyboard-monitor to perform tasks [7]. The co-located condition of users sitting around a single desktop computer to work collaboratively came across well documented problems such as inadequate space for collaborators to perform their task in various parts of the workspace [87]. These problems get more complicated when adding the distribution factor of users being physically separated and using more than one connected computer to work remotely and collaboratively [101]. Efforts to maintain remote collaboration tended to exploit conventional interaction of the traditional mouse-keyboard-monitor to facilitate common workspaces, however, these projects revealed the same problems as in the co-located condition in addition to the problem of users losing awareness of each other's activities [87, 90].

Multi-touch tabletops are investigated for they effectively aid their users in working collaboratively as they intuitively provide a natural multi-user interface [150]. The user interface of conventional software applications is designed traditionally as a single user system that presents other users and their activities in an unclear manner [7, 151]. Performing a certain task collaboratively needs a clear computerised support with a good user-centred interface that should allow and assist the collaborative interactions among users [142, 134]. Multi-touch interfaces can accommodate more than one user concurrently, which is particularly useful for collaborative work.

Adding the distribution factor has its implications on any software regardless of the platform [101]. Maintaining awareness and facilitating communication among collaborating users are two of the most significant obstacles that face remote collaborative software designers. Several studies have shown how multi-touch tables can be used in distributed configuration, and have reported the discovered problems and some proposed solutions for them (e.g. VideoArms [133]).

One interesting topic in collaborative work is multi-player games. They offer enormous potential for collaborative activities and shared experiences [81]. Furthermore, they provide the users (players) a more flexible and creative set of actions. Implementing multi-player games over multi-touch surfaces is not widely studied as other fields. That is the main reason of selecting this field of software as the instrument for this research.

1.1 Motivation and Context of Work

The proposed research shall consider some HCI (human-computer interaction) aspects that are inherent in remote collaboration when using multi-touch tabletops. These aspects fall in three main areas of study: PERFORMANCE, COLLABORATION, and USABILITY. These areas shall be the major criteria of comparison between the co-located and distributed conditions (or scenarios)[1]. Some of the aspects being studied are efficiency, accuracy, equity of participation, and satisfaction. A multi-player game is designed and implemented to work in both configurations: co-located and distributed. Users participated in a two part experiment to analyse the differences between the two conditions.

Studying these HCI aspects can reveal interesting findings about how users interact with such applications in co-located and distributed scenarios, and that can help in suggesting recommendations and guidelines for multi-user applications designers for multi-touch surfaces.

[1] The terms *condition* and *scenario* are used interchangeably in this thesis.

1.1.1 Assumptions

- Networking techniques are not studied in this research; the tables used are connected to display the same content to distributed users as described in Chapter 4
- Gender, age, and education level are not considered in the evaluation, although they are presented in results
- The implemented game is only used as an instrument for collaborative work. Other aspects of computer games, such as graphics, effects, or genres, are not considered in this research

1.2 Objectives

This section presents the objectives of this research which include finding out whether there is a significant difference in the mentioned HCI aspects between the co-located and the distributed conditions. Previous researchers have studied such differences [22, 140], however, the objective of this research is different in that it focuses on the HCI aspects within the context of multi-player games.

Differences in performance, collaboration, and usability between the co-located and distributed conditions are thoroughly analysed in addition to the differences in the relationships among the aforementioned areas. This shall give the evidence to support the conclusions presented at the end of the research, which might be considered by software engineers when designing similar collaborative software environments.

1.3 Approach

Repeated-Measures (within-subject) experimental design has been used in this research. This design is more economic and helps in minimising the sources of random variations [42, 78]. Thirty two (32) participants were used for the experimental sessions. Each participant is exposed to both experiment conditions: *co-located* (same table) and *distributed* (two different tables). The order of conditions in which a group is playing is randomised among the groups to counterbalance the effect of conditions order. The task (game) that is given in both condition is similar in complexity, details, and time allowance. Data has been collected in each session from both conditions to be analysed and compared for similarities and differences.

In co-located condition, the two players use the same table to play the game. They work together towards the same target and they are allowed to verbally communicate and discuss their plan and ask each other for help or offer help to each other (Figure 1.1a).

On the other hand, in the distributed condition, the two players use physically separated tables connected together via the application. However, they are not allowed to verbally talk to each other nor to directly look to each other's table. The application provides messaging mechanism for the players to communicate with each other by asking or offering help and by accepting or rejecting help (Figure 1.1b).

(a) *Co-located* **(b)** *Distributed*

Figure 1.1 – Two different collaboration scenarios

The experimental session is video recorded in each condition, and the participants are asked to fill in a questionnaire after they finish each condition of the experiment. Another invaluable source of data is the system logs that capture all internal interactions with different parts of the game interface and the usage of the messaging communication system.

Chapters 3 and 4 shall present the methodology and system design for this research in greater detail.

1.4 Criteria for Success

In order for this study to succeed, the results of the experimental work is evaluated through statistical analysis. Statistical analysis methods[2] require a set of hypotheses to be validated. These hypotheses are generated from the research questions which are important to be answered to reach the conclusions of this research. The proposed research questions are concerned with the HCI areas that were mentioned previously. These areas are:

1. User's performance
   a) Efficiency: a measurement of how fast a task can be completed; or, in other words, how long did it take a participant or a group to accomplish a given task
   b) Accuracy: a measurement of how precise and effective are the results generated by the participants in a given task
2. Users collaboration
   a) Styles: the collaboration styles that are adopted by the users during their group work
   b) Communication: the factors that affect users' communication during their group work
   c) Contribution balance: a measurement of equity of participation between the users during their group work
3. System usability
   a) Satisfaction: the user subjective satisfaction with the interaction experience
   b) Ease of use and learn: how easily the user can learn to interact with the new system and to complete the given task
   c) Physical and cognitive demand: the level of physical or cognitive requirements that the system exerts on users

For each area, a set of research questions with associated hypotheses are introduced, and will be answered and validated in later chapters (5 and 6). The following subsection briefs the proposed research questions[3].

[2] Discussed in Chapter 3.

[3] Research Question is denoted by RQ.

1.4.1 Research questions

- ***RQ 1:*** Does group performance differ between the co-located and distributed scenarios?
  - ***RQ 1.1:*** Does efficiency differ between the co-located and distributed scenarios?
  - ***RQ 1.2:*** Does accuracy differ between the co-located and distributed scenarios?
  - ***RQ 1.3:*** Do correlations among performance sub-factors differ between the co-located and distributed scenarios?
- ***RQ 2:*** Does participants collaboration differ between the co-located and distributed scenarios?
  - ***RQ 2.1:*** Do collaboration styles differ between the co-located and distributed scenarios?
  - ***RQ 2.2:*** Does participants communication differ between the co-located and distributed scenarios?
  - ***RQ 2.3:*** Does contribution balance differ between the co-located and distributed scenarios?
- ***RQ 3:*** Does system usability differ between the co-located and distributed scenarios?
  - ***RQ 3.1:*** Does satisfaction differ between the co-located and distributed scenarios?
  - ***RQ 3.2:*** Does ease of use and learn differ between the co-located and distributed scenarios?
  - ***RQ 3.3:*** Does physical and cognitive demand differ between the co-located and distributed scenarios?
  - ***RQ 3.4:*** Do correlations among usability sub-factors differ between the co-located and distributed scenarios?
- ***RQ 4:*** Do the internal relationships among the HCI aspects differ between the co-located and distributed scenarios?
  - ***RQ 4.1:*** Do the internal relationships among the sub-factors of performance and collaboration differ between the co-located and distributed scenarios?
  - ***RQ 4.2:*** Do the internal relationships among the sub-factors of performance and usability differ between the co-located and distributed scenarios?
  - ***RQ 4.3:*** Do the internal relationships among the sub-factors of collaboration and usability differ between the co-located and distributed scenarios?

1.5 Thesis Outline

The thesis contains seven chapters, with this one being the first. Below is a briefing of what is expected in each chapter.

Chapter 2 (Literature Review): Provides an overview of the research literature related to human-computer interaction in multi-user environments as well as a briefing of the multi-touch technology and its potential in the computer supported collaborative work. Distribution effects on group work are also described and used as a building unit of this research. And finally, a high level review of multi-player games relevant issues are introduced with focus on the collaborative games.

Chapter 3 (Method): The methodology adopted for this research is presented, including a discussion of the study design, analysis approaches and techniques, and the data sources used. The analysis procedure is explained to show how the research questions introduced in the beginning of this research are going to be answered. Finally, this chapter shall also present the experimental design which was employed to build the environment and the software application that were used during the experiment sessions with participants.

Chapter 4 (System Design): Presents the design of the software used in this research. First, the game scenario is explained to set the objectives of the application. A high level architecture of the application is presented to show how the major components are put together. The user interface is discussed and the interactions needed with the application are also explained with a briefing of the services implemented to support that.

Chapter 5 (Data, Analysis, and Results): Presents the results produced by analysing the data that has been collected during the experimental work sessions. Results depend heavily on statistical analysis as the main source of supporting evidence of the research hypotheses. For each one of the study areas, a briefing of the findings is presented in the form of descriptive statistics, then the hypotheses related to the area are tested by comparing the relevant data in both scenarios. A correlation analysis is also carried out to find out the effect of the experimental condition on the internal relationships among the sub-factors of the research's three areas.

Chapter 6 (Discussion): discusses the impact of physical position of participants (*col-located* and *distributed*) on the HCI aspects introduced throughout this research. The discussion is based on the findings presented in the previous chapter in order to draw conclusions related to the three areas of the research: PERFORMANCE, COLLABORATION, and USABILITY. The discussion structure shall be built around the proposed research questions in order to answer them within the context of the research and its background of previous work.

Chapter 7 (Conclusions): Concludes the research and presents the contribution of the research including some potential implications on designing similar software applications in the future. It also measures the success of the research by checking the research questions answers. The limitations of the research are also presented, and finally a set of suggested future work is listed.

2 Literature Review

This chapter reviews previous research that have been done on the topics related to this thesis, mainly the *HCI* and *CSCW*. It starts by describing the major research areas in human-computer interaction (HCI). That shall include a brief coverage of the research background in HCI area, how the user interfaces evolved and how it is relevant to this study, and a description of the interaction styles that are followed when users interact with software user interfaces. The importance of system usability and how it is analysed and measured are presented to establish the basis for the main parts of this research. A briefing of the multi-touch tabletops technology and how it is used in the collaborative work scenarios is presented as well. Collaborative work is the main focus of this research, therefore, group work and computer supported collaborative work (CSCW) are described with their role in modern group-oriented frameworks. Because multi-player games were selected as the case to study the group collaborative work, computer games and how they aid in studying user engagement and collaboration are presented in this chapter. The distribution of users is the major input factor that this research is going to analyse its effects; therefore, previous studies of user distribution are also described considering the CSCW and multi-player games.

2.1 Human Computer Interaction (HCI)

Computers started to become more popular and available to most people in the early 1980's when companies like Apple and Microsoft adopted more user friendly interaction methods with computers[1]. These methods were basically the implementation of Graphical

[1] This is with reference to the start of the widespread of desktop personal computers. Technically, Xerox PARC's Alto computer (1973) can be considered as the direct ancestor of desktop computers with a basic GUI and a mouse, but it was not popular enough to consider its effects on the market.

User Interface (GUI) and the introduction of the mouse as a means of input based on direct visual manipulation of objects on screen (Baecker et al. [9]). Computer designers and researchers are continuously investigating the interaction ways between computers and users. The most important objective of these efforts is to come up with best solutions for users/computers interaction. A new field of research emerged as a result of this, that is, the Human Computer Interaction, or simply HCI.

Research in HCI has been spectacularly successful and has fundamentally changed computing. One example is the graphical interface used by Microsoft Windows, which is loosely based on Apple Macintosh design that used interaction principles formulated at Xerox PARC, which in turn is based on early research at the Stanford Research Laboratory and at Massachusetts Institute of Technology (Myers [96]). Even the remarkable growth of the World Wide Web is a direct result of HCI research: applying hypertext interaction with text to web browsers allows one to traverse a link across the world with a click of a mouse [96].

The mass personal computer markets have meant that sales of computers are more directly tied to the quality of their interfaces than in the past. The result has been the gradual evolution of standardised interface architecture. Along with these changes, researchers and designers have begun to develop specification techniques for user interfaces and testing techniques for the practical production of interfaces (Hewett et al. [58]).

HCI studies both the machine side and the human side. From the technical machinery point of view, it arose as a field from intertwined roots in computer graphics, operating systems, ergonomics, industrial engineering, cognitive engineering, and the systems part of computer science. Computer graphics was born from the use of CRT and pen devices very early in the history of computers. This led to the development of several HCI techniques. Many techniques date from Sutherland's Sketchpad PhD thesis in 1963 that essentially marked the beginning of computer graphics as a discipline (Sutherland [131]). Work in computer graphics has continued to develop algorithms and hardware that allow the display and manipulation of ever more realistic-looking objects. Computer graphics has a natural interest in HCI as "interactive graphics" (e.g., how to manipulate solid models in a CAD/CAM system). A related set of developments helped to come up with a number of important building blocks for human-computer interaction. Some of these building blocks include the mouse, bit-mapped displays, personal computers, windows, the desktop metaphor, and point-and-click editors. Work on operating systems, meanwhile, developed techniques for interfacing input/output devices, for tuning system response time to human interaction times, for multiprocessing, and for supporting windowing environments and animation. This strand of development has currently given rise to "user interface management systems" and "user interface tool kits" [58, 9].

From the human perspective, HCI derives from the problems of designing equipment operated by humans. Many problems faced by those working on human factors had strong sensory-motor features (e.g., the design of flight displays and controls). The problem of the human operation of computers was a natural extension of classical human factors concerns, except that the new problems had substantial cognitive, communication, and interaction aspects not previously developed in human factors, forcing a growth of human factors in these directions [35, 144, 78]. Ergonomics is similar to human factors, but it arose from studies of work. As with human factors, the concerns of ergonomics tended to be at the sensory-motor level, but with an additional physiological flavour and an emphasis on stress [9]. Human interaction with computers was also a natural topic for ergonomics, but again, a cognitive extension to the field was necessary resulting in the current "cognitive ergonomics" and "cognitive engineering" (Veer [144]). Because of their roots, ergonomic studies of computers emphasise the relationship to the work setting and the effects of stress factors, such as routines of work, sitting posture, or the vision design of the displays.

Industrial engineering arose out of attempts to raise industrial productivity starting in the early years of the 20th century [58]. The early emphasis in industrial engineering was in the design of efficient manual methods for work (e.g., a two-handed method for the laying of bricks), the design of specialised tools to increase productivity and reduce fatigue (e.g., brick pallets at waist height so bricklayers didn't have to bend over), and, to a lesser extent, the design of the social environment (e.g., the invention of the suggestion box). Interaction with computers is a natural topic for the scope of industrial engineering in the context of how the use of computers fit into the larger design of work methods (Orlikowski [105]).

Cognitive psychology derives from attempts to study sensation experimentally in the 1950's, an infusion of ideas from communications engineering, linguistics, and computer engineering led to an experimentally-oriented discipline concerned with human information processing and performance. Cognitive psychologists have concentrated on the learning of systems, the transfer of that learning, the mental representation of systems by humans, and human performance on such systems (Landauer [76]). Basing interaction on pre-existing real world knowledge and skills may reduce the mental effort required to operate a system because users already possess the skills needed (Jacob et al. [66]).

HCI research helps in introducing new interface designs and interaction models, however, these research efforts cannot easily break through the market requirements. HCI researchers have developed and evaluated a variety of innovative novel interaction techniques but few have been adopted in the marketplace (Beaudouin-Lafon [16]). Two major barriers restrict wider spread of interaction research. First, although HCI researchers have created a variety of novel interaction techniques and shown their effectiveness in the lab, such experimental designs are insufficient. Software developers need models, methods and tools that allow them to transfer these techniques to commercial applications. Second, WIMP user interfaces (presented in Subsection 2.1.1.1) have been so stable and so universally adopted over the past three decades that the user's cost of change is very high [16].

2.1.1 Towards GUI tabletop metaphor

Graphical User Interface (GUI) was not isolated from the evolution of the HCI research. Actually, it was a crucial part of it. With the added power and complexity of computer hardware, GUI came into the scene as a natural replacement for the old text-based interaction methods such as command line input, at least for the normal daily users (Eberts [35] and Beaudouin-Lafon [16]). A well designed GUI allows a computer user to smoothly move from application to application, as well as making an application easy, practical, and efficient to use (Jansen [68]). GUI is more intuitive when it comes to the user learning curve [9, 96]. It provides the user with several cues as to what options it provides simply by the way it looks. Most users become proficient with GUI utilities without ever having to read through their help files (Microsoft [84]). A GUI offers graphical icons, and visual indicators, as opposed to text-based interfaces, typed command labels or text navigation to fully represent the information and actions available to a user. The actions are usually performed through direct manipulation of the graphical elements; an important interaction style that will be discussed later in Subsection 2.1.2.1 of this review.

Jansen [68] stated that the goal of any GUI is to allow the user to work through the computer and application to concentrate on the primary cognitive task. The user should not be deeply concerned with the user interface as the attention devoted to the interface may interfere with the main task. It is crucial that the GUI is consistent and predictable so that the user treats the interface as reality. A computer is a complex abstract system and so it is important to create the illusion that the system was organised enabling the user to use it with relative ease, and without having to remember a series of abstract rules (Shneiderman [128]). The main component used to do this was the creation of visual and functional metaphors, which included features like the trash can and the file folders. This assists what is known as "reactive cognition" where user understands how to use the computer through interacting with the interface. A successful metaphor should be simple and understandable without the user having to memorize or learn a series of commands (Kay [70]). A user interface metaphor is a collection of visuals and actions that utilise specific knowledge that users already have of other domains. The purpose of the interface metaphor is to give the user instantaneous knowledge about how to interact with the user interface (Yousef [156, 157]).

Metaphor is a term that is used in designing user interfaces to denote that a concept familiar to the intended set of users of a particular application is borrowed to represent, or re-frame, a computer operation at the software interface. A visual icon can be used to represent this computer operation; the image depicts a familiar concept. Interface metaphors act as cognitive shortcuts by helping users build on already existing mental models of familiar concepts when learning new systems (Yousef [157]) and (Jacob et al. [66]). The trash can icon is an example of an interface metaphor. The trash represents a computer function similar to the one for which people use an ordinary trash in their offices. A trash can is ideally used to discard unwanted objects. In software context, the trash icon allows the user to get rid of unwanted electronic files [37, 157].

Software designers usually select interface metaphors to simplify the user tasks by building on the user's existing knowledge from a familiar concept. A metaphor can be regarded as a mapping between the source and the target domains, such as the *desktop* metaphor (Green and Jacob [47]) and the *tabletop* metaphor (Müller-Tomfelde et al. [94]). The source domain is the one used to describe the new system and with which the users of the software are familiar. The target domain is the one that needs to be described and about which users know little (Saffer [117]) and (Erickson [37]). A semantically efficacious interface metaphor is one which users find comprehensible and are able to generate correct inferences about the intended purpose of the metaphor. Further, an efficacious metaphor is one with which users feel comfortable while using any function that is metaphor-supported (Yousef [156, 157]).

One of the most popular user interface metaphors is the *desktop* which started to dominate the user interface designs in the 1980s (Green and Jacob [47]). It has been almost universally assumed that a desktop direct manipulation user interface is the best style of user interface for all applications. This point is supported by the facts that almost all user interface design and implementation support only this style of interaction, and that existing user interface style standards only address desktop user interfaces. Thus, the term post-WIMP (see Subsection 2.1.1.2) has been used to refer to any user interface style that is not based on the desktop metaphor (Beaudouin-Lafon [15]). In the desktop metaphor, the computer screen is treated as if it is a physical desktop, on which objects such as documents and folders of documents can be placed.

The obvious metaphor that is more related to the topic of this research is the use of the *tabletop* term to describe the horizontal workspace area that a multi-touch screen provide to its users (Besacier et al. [19]). People are used to work collaboratively around tables utilising the space of the horizontal table surface. Moving to the digital tables is considered a very natural transition given that a proper interface and interaction styles are implemented (Müller-Tomfelde et al. [94, 95]).

In the next two subsections, the two types of interfaces, WIMP and post-WIMP, are described with justification of why interfaces are transitioning to the latter one to overcome the limitations that WIMP interfaces suffer from.

2.1.1.1 WIMP interfaces

The acronym WIMP stands for Windows, Icons, Menus, and Pointing. It denotes a direct manipulation style of interaction using these four elements and usually accompanied with desktop metaphor. WIMP are visualised concepts that bring forth a certain action or an action space (Jansen [68]). WIMP interfaces have been dominant since the late 1980's to the extent that the terms WIMP and GUI are usually used interchangeably in the HCI literature.

WIMP interfaces revolutionized computing, making computers accessible to a broad audience for a variety of applications (Beaudouin-Lafon [15]). Lisa computer (1983) and the Macintosh (1984) were the first mass-produced WIMP based machines. Moreover, with the rapid rise of Microsoft Windows, WIMP interfaces have become the de facto interface paradigm (Taylor [137]). WIMP interface uses a physical input device to control the position of a cursor and presents information organized in windows. Available commands are grouped together in menus and can be executed through the pointing device.

In general, WIMP interfaces can be considered as a type of direct manipulation interface (see Subsection 2.1.2.1). However, a WIMP interface may just offer direct access to controls (buttons/menus) but not necessarily manipulate the objects of interest directly; the distinction can be subtle [137, 16]. For example, one may click a button to put an item in a shopping cart rather than dragging the item to the cart. Therefore, WIMP interfaces do not strictly follow the principles of direct manipulation. Instead, they introduce interface elements such as menus, dialogue boxes and scrollbars that act as *mediators* between users and the objects of interest (Beaudouin-Lafon [15]). This matches the experiences in the physical world; for example, people cook with pots and pans, open doors with handles, and turn off lights with switches. The interaction with the physical world is governed by the usage of tools. Direct manipulation of physical objects of interest occurs when they are brought into the current context of operation, before they are manipulated with the appropriate tools (Guiard [49], Beaudouin-Lafon [15]).

WIMP Interfaces have a number of standard elements. Other elements are prevalent, but optional such as graphical displays and metaphors (Taylor [137]). For example, a WIMP can be implemented in a text-based system but graphical displays are often assumed. Metaphors do not have to be used, but often are.

Taylor [137] specified four standard WIMP elements, which are:

Windows: A window is usually a rectangular portion of the screen on a monitor that features some of the content (for example, a text file or an image) seemingly independent of the rest of the screen. That mimics the sheet of paper that presents the information in front of the viewer. Some of the popular features of a window include open, close, move and resize. Several windows can be opened and stacked or tiled which is a very useful feature in a multitasking application.

Icons: The icon is a small graphical representation of an object inside the WIMP interface. These objects can be files, programs, websites, or commands. Icons are a quick way to execute commands, open documents, and run programs. Icons are also very useful in exploring the system searching for different objects as they can be visually categorized according to the type of object they are representing.

Menus: Menus allow the user to execute commands by selecting from a list of options. These commands are executed by selecting them with a pointing device in a GUI. Sometimes, a keyboard can also be used. The menus are convenient because they clearly show what commands are available in the software. Some of the most common types are the drop-down menus and pop-up menus. Toolbars and checkboxes are also special types of menus. A more sophisticated menu is based on the context menu, where the list of available commands changes depending on the status of the application.

Pointing: Pointing is a term used to denote the use of a pointing device to control a "pointer" on the screen. The pointer is used to manipulate others WIMP elements, for example, selecting a command from a menu. This pointer may have different graphical representations that provide a visual aid for the user. For instance, it is shaped like an index finger when it hovers over a hyperlink and shaped like an hourglass to indicate that a task is being performed. The pointing device that becomes the most dominant one is the mouse which became a crucial part of everyday computer usage. Other devices include light pen, trackball, and touchpad.

WIMP style of interaction is intended to reduce the cognitive load to remember the possibilities available, reducing learning times. Other expected benefits of this style are its ease of use for non-technical personnel, both beginners and advanced users (Taylor [137]). Moreover, given the high consistency between applications interfaces, users can transfer their knowledge from one application to another easily because of the standardised WIMP interaction with interfaces (Van Dam [143]). GUI designers usually follow the guidance that the interface should display only what the user needs to perform the task in hand; empirical researchers show that limiting the information to that necessary for the user reduces errors and time to perform tasks (Jansen [68]).

When designing a GUI, designers should keep the objectives of the system in mind and should, generally, avoid needless complexity and useless innovations and concentrate on improvements that enhance performance [68, 15]. However, some types of common actions are not easily done in WIMP, for example, wildcard expressions are not directly supported [137]. Also, a badly designed WIMP interface may result in extreme inefficiency and poor work support. Van Dam [143] listed some of most important limitations of WIMP interfaces and shows how can the next generation of interfaces, known as *post-WIMP*, help to overcome such limitations; these are described in Subsection 2.1.1.2.

2.1.1.2 Post-WIMP interfaces

A post-WIMP[2] interface is one containing at least one interaction technique not dependent on classical WIMP elements (described in Subsection 2.1.1.1) such as menus and icons [47, 143, 66]. Ultimately it will involve all senses in parallel, natural language communication and multiple users. A post-WIMP interface assumes no menus, no forms, no toolbars, and heavily relies on gestures and utilisation of senses (Van Dam [143]), and they often draw upon users object manipulation skills (Jacob et al. [66]).

The leap from WIMP to newer post-WIMP graphical interfaces, which take advantage of novel interaction techniques, requires both new interaction models and corresponding tools to facilitate development (Beaudouin-Lafon [15]). An interaction model is a set of principles, rules and properties that guide the design of an interface. It describes how to combine interaction techniques in a meaningful and consistent way and defines the “look and feel” of the interaction from the user’s perspective. Properties of the interaction model can be used to evaluate specific interaction designs [15].

Some researchers, such as Beaudouin-Lafon [16], believe that WIMP interfaces have reached their limits in the face of three major challenges: (1) the exponential growth in the amount of information each individual user deals with; (2) the distribution of this information over multiple computers and devices; and (3) the growing range of computer users, with their wide variety of skills, needs and expectations.

Post-WIMP interfaces emerged as a new style of interaction to overcome the limitations that WIMP interfaces suffer from. These limitations are summarised below as mentioned by Van Dam [143] and Biström [20]:

- Interface becomes harder to learn as applications get more complex because of the widgets[3] and features, each of which is individually easy to learn but in the aggregate creates complexity
- Users spend too much time manipulating the interface, not the application
- WIMP GUIs, with their 2D representation objects, were designed for, and well suited to, 2D applications such as word processing, media viewing, and spreadsheets. When

[2] Or non-WIMP.

[3] Widgets are basic visual building blocks which, combined in an application, hold all the data processed by the application and the available interactions on this data (Baecker et al. [9]).

the information is more complex than 2D representation, the mapping between the information and 2D objects is much less natural
- Mouse and keyboard are not suited to all users; for example, users with disabilities and injuries may find it difficult to efficiently use the mouse and the keyboard
- WIMP interfaces do not take advantage of all human senses other than the visual sensory. Speech, hearing, and *touch* can add a tremendous amount of interaction aids and feedback. It is difficult for us to communicate in the physical world without speech, sound, and touch as well, and that is why WIMP interfaces are considered less natural

Some examples of post-WIMP interfaces include gestural-based systems, haptic devices, *multi-touch tabletops*, voice recognition devices, and eye tracking sensors. The RBI (Reality Based Interaction) concept, introduced in Subsection 2.1.3, can work as a framework to analyse the design of post-WIMP interfaces (Jacob et al. [66]). That can help in assessing and evaluating the user interface designs of new applications that utilise these new paradigms in interaction design.

Green and Jacob [47] suggested the following five characteristics as the most important features of a post-WIMP interface:

1. *High bandwidth input and output*: contrary to classical WIMP interfaces where there is, usually, one input event generated at a certain interval of time [20], most of the styles of post-WIMP interaction require high bandwidth for input and output to accommodate the synchronous multi-input sources and multi-output channels
2. *Many degrees of freedom*: post-WlMP user interfaces have a large number of degrees of freedom in both the underlying application and the interaction devices
3. *Real-time response*: all of the post-WIMP interaction styles rely on real-time response to the user's actions
4. *Continuous response and feedback*: a post-WIMP user interface must be continually responding to the user's actions, since there isn't the well defined notion of a *command* that occurs in the WIMP user interfaces
5. *Probabilistic input*: since immediate response is very important, the user interface may need to guess what the user is trying to achieve in order to produce timely feedback. Occasionally these guesses will be wrong, and the user interface will need to correct its mistakes

The previous list of characteristics suggests that post-WIMP user interfaces could be called *highly interactive user interfaces*. It is essential that the user's set of interaction techniques with a post-WIMP interface should not be restricted, no matter what state the application is in, and that is why post-WIMP applications need to be truly interactive by considering those characteristics [47].

Post-WIMP interaction techniques help users to explore large quantities of visual data and make sense of it by simplifying the navigation among the different parts of the interface (Beheshti et al. [17]), and providing easy and direct ways to enter data and display outputs (Beaudouin-Lafon [15]). A key aspect here is the strong coupling between user actions and system response. Both navigation and input/output are usually multi-dimensional tasks: the user wants to control several dimensions simultaneously to navigate along different parts of the interface. This requires highly flexible navigation and input methods [15]. For example, a movable, rotatable, and resizeable user area that can be used by the user anywhere on the table surface and from any side of the table as well. The last example suggested an interaction feature that is very similar to the user's panel used in the application built for this research (see Chapter 4).

Multi-touch tabletops represent a very good example of post-WlMP interfaces. Two-handed input studies shows that using a pair of touch-sensitive areas to interact with the interface can result in improved performance (Hinckly et al. [61, 23] and Kin et al. [73]). When working on a tabletop, there are many fundamental differences in the user input paradigm that challenge conventional WIMP assumptions. These differences are summarised by Shen [123] in the following points:

- The input area of any given user/point is larger, and a different shape, than the single pixel defined by a mouse pointer
- Windows/widgets may be rendered off-axis (i.e. rotated)
- A single user may be touching multiple UI-controls/screen points simultaneously
- Multiple users may be touching the same UI-controls/screen points simultaneously
- Multiple users may be touching different UI-controls/screen points simultaneously
- Multiple users may be entering text from different keyboards (soft or hardware) simultaneously

With these differences, the limitations of WIMP interfaces become more obvious which justifies the need for more innovative interaction styles that are found within the post-WIMP interfaces. Multi-touch tabletops inherently support multiple touches, multiple users, and rotating the digital artefacts on their interfaces [123, 152, 43]. Moreover, they support interaction by hand gestures, which is an intuitive and natural way of interaction that helps users to easily manage their artefacts without the need for additional external devices such as mice and styli (Kruger et al. [75] and Wigdor et al. [151]). There are even more promising studies that integrate multi-touch tables with sophisticated environments, such as controlling the tabletops in a classroom using body movements captured by Microsoft Kinect (Durham University [3]), and integrating direct manipulation interaction[4] with 3D environment (Möllers et al. [86]).

Multi-touch tabletops have their own set of problems, though. For example, it is difficult to identify the user who touches the tabletop surface at any given time when multiple users are using the same table concurrently. One approach to overcome this problem is by assigning well defined areas on the interface for each user (Scott et al. [119] and Tuddenham et al. [140]), which is the approach used in this research's application. Another common problem in most of the touch devices is the text entry. Virtual keyboards are the dominant method for text entry in touch screens, however, they suffer from inefficiency and inaccuracy (Edelmann et al. [36]), and can cause many troubles when multiple users try to use them at the same time (Isenberg et al. [64] and Basheri et al. [14]). Connecting physical keyboards to the tables (Tuddenham et al. [141]), or mixing physical and virtual keyboards (Kharrufa et al. [72]) could be possible solutions for such a problem.

2.1.2 Interaction styles

Interaction with computers has evolved from the first generation of command line, to the second generation of direct manipulation, to a new generation of emerging post-WIMP interaction styles (Jacob et al. [66]). The concept of interaction styles refers to all the ways the user can communicate or otherwise interact with the computer system. Shneiderman [128] defined the types of usual interaction styles as command language, form filling, menu selection, natural language, and direct manipulation. Interacting with the user interface using a touch screen (and hence the multi-touch tabletops) can be considered as a form of direct manipulation interaction (Shneiderman [127]). Actually, it is even more "direct" than other interaction techniques, such as mice and touch pads, because the user manipulates the desired user interface object directly by "physically"

[4] Direct manipulation interaction is described in Subsection 2.1.2.1.

touching it on screen by hand or stylus [127]. Direct manipulation interaction style is explained in more detail in Subsection 2.1.2.1.

Nacenta et al. [99] showed how the way that users interact with tabletop groupware systems can affect how they collaborate with each other. Their findings show significant differences across techniques in terms of conflicts, reaching patterns, object transfer, group performance, and user preference. The main result of this work is that no one interaction technique is best for all tasks and all tabletop situations. For example, direct-touch techniques such as drag-and-drop reduce resource conflicts, but at the price of being much less effective when used for reaching distant artefacts. Another example shows that miniature views such as the radar view were surprisingly effective for a game task, although in a design task the radar did not provide enough awareness information to be successful (Ha et al. [53]).

Three dimensions were specified to classify user interaction methods with tabletop surfaces as described by Nacenta et al. [99]:

1. **Location of input:** different interactions allow users to provide input from two possible locations: the local space or the shared space. The local space is the area near the user, and shared space is the area between users that is visible to all of them which may not be always easily accessible. Local and shared spaces may overlap depending on the position of different users. The relatively large surface area of the tabletop allows direct input into the workspace. Direct input can force group to share input space in order to manipulate objects on the table [99, 97].
2. **Location of feedback:** visual information (feedback) provided by an interaction allows users to adjust and correct their actions. This interaction feedback can be displayed through the shared space, local space, or both. Local feedback is used by miniature view techniques such as radar views, which allow users to interact with all surface objects. Miniature view techniques facilitate both the direct input and access to the entire work area; however, this view may not provide sufficient resolution to perform some tasks. Tabletops have the advantage that users can share representations of objects (Nacenta et al. [98]). An important note is that users do not need to use tabletops if they only want to provide private representations of workspace as multiple miniature views in personal displays would suffice. Consequently, tabletop miniature views should be used in combination with shared visual representation, which provides feedback both locally and shared [99].

3. **Embodiment:** embodiment is a real or virtual representation of the user's body in the system, and is a valuable mechanism for the representation of presence, location, and activity information. Embodiments can vary widely in form and size according to different forms of interaction. The two main aspects that make embodiments different are how literal the representation is, and how large. In shared input space, embodiment can be full-size with literal representations because of the use of physical bodies and arms (Ha et al. [53]). These techniques have intrinsic advantages of awareness as the system does not have to represent the users points of action, and the identities of different users are easy to determine. However, other techniques require virtual representation of embodiment, i.e. digital representations that are drawn in the workspace such as cursors. Although cursors can convey awareness, they are much smaller than physical arms, and the user-cursor relationship is not always clear. Colour is usually used to differentiate the groupware users cursors, and even richer representations such as photographs are also possible. Some representations go beyond that by drawing a line between the cursor and the user virtual place, providing a visual link between each cursor and its owner [99]. This linking technique is used in the application built for this research as described in Chapter 4.

In addition to the dimensions described above, interaction with user interface can be classified into interaction paradigms. Beaudouin-Lafon [16] suggested three primary interaction paradigms to be considered:

1. Computer as tool
2. Computer as partner
3. Computer as medium

The computer as tool paradigm extends human capabilities through a (very sophisticated) tool. Direct manipulation and WIMP interfaces fall into this category. The computer as partner paradigm embodies anthropomorphic means of communication in the computer, such as natural language, so that users can delegate tasks. Agent based interaction and speech based interfaces fall into this category. The computer as medium paradigm uses the computer as a medium by which humans communicate with each other. Email, chat and video-conferencing fall into this category. Human-Computer Interaction focuses on computer as tool, Artificial Intelligence focuses on computer as partner, and Computer Supported Cooperative Work focuses on computer as medium. Note that these paradigms rely on two sets of skills: the ability to create and use artefacts (computer as tool and computer as medium), and the ability to communicate with each other through language (computer as partner and computer as medium). The unique challenge here is to create new tools that both augment and complement human capabilities (Beaudouin-Lafon [16]).

To enable software designers to use interaction techniques in their user interfaces, interaction styles are put into models (Carroll [25]). The purpose of an interaction model is to provide a framework for guiding designers, developers and even users to create interactive systems (Beaudouin-Lafon [16]). Interaction models can be evaluated along three dimensions:

1. Descriptive power: the ability to describe a significant range of existing interfaces
2. Evaluative power: the ability to help assess multiple design alternatives
3. Generative power: the ability to help designers create new designs

An interaction model can range from high-level design guidelines, such as the three principles of direct manipulation (Shneiderman [126, 128]), to detailed rules such as the Apple Human Interface Guidelines [28]. Beaudouin-Lafon [16] mentioned that high-level models tend to have good descriptive power but poor evaluative and generative power, while low-level models tend to have poor descriptive and evaluative power, but higher generative power. A good interaction model must balance between generality (for descriptive power), concreteness (for evaluative power) and openness (for generative power). It is important to know that the quality of the interaction model itself does not guarantee the quality of the resulting designs [128, 25]. As with programming languages, where a programmer can write terrible programs with a good language, a designer can create terrible interfaces with a good model.

2.1.2.1 Direct manipulation interaction

Direct Manipulation moved interfaces closer to real world interaction by allowing users to directly manipulate objects rather than instructing the computer to do so by typing commands (Jacob et al. [66]). Direct manipulation is a central theme in interface design. It captures the idea of “direct manipulation of the object of interest” (Shneiderman [128]), which means that objects of interest are represented as distinguishable objects in the UI and are manipulated in a direct fashion. Direct interaction style can be traced back to Sutherland’s sketchpad (Sutherland [131]) when he demonstrated in his work the first real GUI application that can be directly interacted with. Indeed, direct manipulation moved interfaces closer to real world interaction by allowing users to directly manipulate objects rather than instructing the computer to do so by typing commands [66].

Direct manipulation systems visually present tasks because of the visibility of the objects of interest. They are easy to learn compared to command-line systems that use complex syntax to interact with. Usually, direct interaction encourages exploration with errors being avoided more easily because of the intuitive metaphors used in designing the user interface. To give an example of this interaction style, let's consider the “move file” operation. In the command-line theme, the user needs to write a “move” command that moves the file from its original directory in the file system to another directory. To accomplish this operation, it is assumed that the user knows the syntax of the command, how to navigate between directories in the file system, and how to diagnose an error if happened; obviously, these assumptions are not always met especially for a naive user. On the other hand, using a GUI/Mouse as a mean of direct interaction, the user will just click on the file to be moved, drag it to the desired destination, and drop it there. What the user needs to know is just the “drag-and-drop” metaphor which intuitively mimics file movement in real world. With such a style of interaction, syntactic errors are minimised to a very low level or even cancelled, and semantic errors can be easily recovered (Baecker et al. [9]).

Shneiderman [128] specified three principles for direct manipulation interaction:

1. Continuous representation of the objects and actions of interest with meaningful visual metaphors
2. Physical actions or presses of labelled buttons, instead of complex syntax
3. Rapid incremental reversible operations whose effect on the object of interest is visible immediately

Shneiderman [128] has also described the benefits of adopting these principles when designing the user interface. These benefits include:

- Novices can learn basic functionality quickly
- Experts can work rapidly to carry out wide range of tasks
- Users can immediately see their actions results and task progress
- Users experience less anxiety because they know that their actions are reversible

However, Shneiderman [128] specified some problems with direct manipulation designs. These are summarised in the following points:

- Direct manipulation designs may consume valuable screen space causing information to be rendered off-screen, and thus require the user to scroll or do multiple additional actions
- Users have to learn the meaning of the visual representation of different objects on the interface
- Visual representation might be misleading if not designed carefully
- For experienced typist, using the mouse can be slower than typing in the command line

Because of the above benefits and problem, the user interface must be designed very carefully, and tested thoroughly by potential users as they will be the real consumers of the interface and their feedback must be considered.

Direct manipulation is an inherent part of the touch-based interfaces (Shneiderman [127]). When designed carefully, a multi-touch interface can provide a very powerful means of interaction that can be easily comprehended and enjoyed by users because they combine the advantages of the post-WIMP and direct manipulation interaction styles.

2.1.3 Reality based interaction

Jacob et al. [66] introduced the concept of Reality Based Interaction, RBI, as a framework to apply real world themes to analyse the design of post-WIMP interfaces. Researchers often leverage users knowledge and skills of interaction with the real world. This knowledge includes naïve physics, as well as body, environment and social awareness and skills. Although the researchers did not explicitly refer to these reality-based themes, they made design choices reflecting the same principles. The suggested real world themes are:

Naïve Physics (NP): People have common sense knowledge about the physical world. For example, employ physical metaphors that add the illusion of gravity, mass, rigidity, springiness, and inertia to graphical widgets.

Body Awareness & Skills (BAS): People have an awareness of their own physical bodies and possess skills for controlling and coordinating their bodies. People learn the skills to coordinate movements of their limbs, heads, eyes, etc. in order to do certain things like walking. Post-WIMP interfaces support an increasingly rich set of input techniques based on these skills. Two handed interaction and gestures are considered of this category.

Environment Awareness & Skills (EAS): People have a sense of their surroundings and possess skills for negotiating, manipulating, and navigating within their environment. They develop many skills for navigating within and altering their environment. In the context of new emerging interaction styles, interfaces use reference objects and artificial landmarks to provide users with clues about their virtual environment and simplify size and distance estimations in that environment. Post-WIMP interaction styles often draw upon users object manipulation skills.

Social Awareness & Skills (SAS): People are generally aware of the presence of others and develop skills for social interaction. These include verbal and non-verbal communication, the ability to exchange physical objects, and the ability to work with others to collaborate on a task. Many emerging interaction styles (Post-WIMP) encourage both social awareness and remote or co-located collaboration. For instance, exploit social awareness and skills by representing users presence, by displaying their avatars, and by making the avatars actions visible.

Using the pre-existing knowledge of world interaction can significantly reduce the mental effort required to interact with a user interface because users already have the necessary knowledge (Saffer [117] and Green and Jacob [47]). This helps to accelerate learning and improve performance and exploration. The nature of a tabletop interface makes it very natural to use in a social setting with two or more people [66]. For example, a multi-touch tabletop is used to create applications that are based on naive physics when manipulating objects by hands. Also, consider flicking an object which uses EAS via spatial metaphor; all objects in real world have spatial relationships between them.

However, making an interface a reality-based one is not sufficient. A useful interface cannot entirely imitate the real world, but will necessarily include some unrealistic or artificial features and commands (Shneiderman [129]). In fact, much of the power of using computers comes from ability to go beyond a precise imitation of the real world [66]. That is why there are some trade-offs of RBI, as reality might be jeopardized in favour of other desired qualities such as functionality, efficiency, versatility, ergonomics, accessibility, and practicality.

2.1.4 Multi-touch groupware usability

Usability engineering and analysis is becoming a recognised discipline with established practices and standards (Shneiderman [128]). As software becomes more and more interactive, attention to the needs and preferences of the end user intensifies (Te'eni et al. [138]). Usability is a very broad term that is used in HCI studies. It studies the factors that make a software system effectively, efficiently, and satisfactorily *usable* when users use it to perform the tasks that that system was designed for, taking into consideration that users became more diverse and less technical [138, 1]. Usability analysis can be categorised into three main areas as defined by Lazar et al. [78]. These usability areas (or factors) are taken into consideration in this research, and they are:

1. Satisfaction: the analysis of the user subjective satisfaction with the interaction experience
2. Ease of use and learn: the analysis of how easily the user can learn to interact with the new system and to complete the given task
3. Physical and cognition demand: the analysis of the level of physical or cognitive requirements that the system exerts on users

Multi-touch interfaces have some intuitive features that indicate good usability such as zooming, scrolling, and bi-manual operations. Other features encourage multiple users to interact and uses pressure sensitivity to enhance fine control [54]. For manipulating virtual objects over a multi-user table surface, multi-touch seems to be an ideal approach from a usability point of view. The real challenge will lie in attempts to integrate multi-touch into a wider range of applications. Usability will make or break any such attempts. It seems likely that multi-touch interfaces will succeed in efficiency and satisfaction areas of usability (Ha et al. [53] and Morris [89]). But when it comes to complex tasks, multi-touch interfaces do not seem to provide enough flexibility to be truly easy to learn and work efficiently. There should be implemented mechanism in the interface to help users to avoid making a frustrating actions, such as reaching to each other personal workspace or loosing awareness of each other activity [53]. Simply touching the screen rather than pointing with a mouse will not automatically remove these challenges. Therefore, the designers of multi-touch groupware should be keen to examine the usability implications of these changes.

Groupware usability is defined by Gutwin and Greenberg [50] as "the degree to which a groupware system supports the mechanics of collaboration for a particular set of users and a particular set of tasks." From this definition, it obvious that the collaboration element is a key to a successful groupware and user experience. Gutwin and Greenberg [50] have also suggested that usability analysis should be focused on the following areas when studying groupware; these areas are also based on the usability analysis as defined by the ISO standard 9241 [1]:

Effectiveness: considers whether the activity was successfully completed, and the number of errors made during that activity. A usable groupware system should not prevent collaboration from taking place, and should not cause group members to make undue errors during their group work.

Efficiency: considers the resources (such as time or effort) required to carry out the activity. A good groupware system shall allow the activities of collaboration to proceed with less time and effort than will a system with usability problems.

Satisfaction: considers whether the group members are reasonably happy with the processes and outcomes of each of the activities of collaboration. Satisfaction will sometimes overlap with efficiency and effectiveness (that is, problems in the other areas are likely to reduce satisfaction).

2.1.5 Multi-touch Tabletops

Multi-touch displays are not a very new technology; they have been built in research labs for many years. Research into digital tabletops started in 1993 with a pioneering project called DigitalDesk (Kharrufa [71]). Although the DigitalDesk supported remote collaboration by connecting two systems together, its main focus was on single user interaction with physical desks rather than face-to-face collaboration around tables. Mitsubishi Electric Research Labs, MERL, started a research project in 1999 and created a multi-touch table called DiamondTouch [31]. In 2006, Perceptive Pixel developed wall-sized multi-touch screens that can be used while standing as if they are whiteboards; they are called "Multi-Touch Walls" [55]. Well known large companies have also developed their versions of the technology such as Microsoft's PixelSense [83].

A multi-touch tabletop is a display surface that uses the multi-touch interaction technique to enable users to interact with a computer system by directly making input through "touching" the display itself instead of the traditional input methods (i.e. screen, keyboard, and mouse). Multi-touch denotes a set of interaction techniques which allow users to control graphical user interface with more than one finger, which is a distinguishing feature of these displays. The ability to capture multi-input points means, for example, that a user can use both hands to interact with the display or even more than one user can work together on the same display. By the contrary, the old touch screen technology, which, at a time, became very common on tablet PCs and advanced mobile phone, allow the user to interact with the system by making a single "touch" either by finger or stylus.

When designing a groupware for multi-touch tabletops, a number of guidelines have to be taken into consideration. Several researchers have suggested these guidelines to be used in order to obtain a good usable and collaborative groupware. According to Kharrufa [71], Wallace and Scott [145] adopted the most abstract level of guidelines presenting the factors that are external to the table itself and how they should reflect on the software user interface. These included social and cultural factors, type of activity, duration or temporal factors, ecological factors, and the motivation behind the activity. Studying these factors will affect how the user interface for the multi-touch groupware is going to be designed. For example, professional users who are expected to use the table frequently, will need a more sophisticated user interface on their tables than that on a table in a coffee shop or a classroom.

A less abstract guidelines that are frequently cited are Scott et al.'s [118]. Kharrufa [71] has summarised these guidelines as follows:

- Supporting interpersonal interaction: The system should not cause conversation or visual breakdowns while the users are interacting. Natural interaction can also be supported with an appropriate and friendly physical design for the table
- Supporting fluid transition between activities: This can be in terms of software tools, or hardware/software tools as in switching between using a physical keyboard and a stylus
- Supporting transitions between personal and group work: Dividing the table space in personal and public areas is suggested as a way to support this
- Supporting transitions between tabletop collaboration and external work: Work generated externally should be easy to incorporate in the tabletop environment and vice versa
- Supporting the use of physical objects: Physical objects include pen, paper and/or tangible objects augmented with digital data
- Providing shared access to physical and digital objects: Shared access to physical and digital objects should be provided where it helps in maintaining group focus and facilitates awareness

- Form and configuration: Consideration should be paid to the appropriate arrangement of users and the table shape and size, in relation to the task at hand
- Supporting simultaneous user actions: Parallel interaction should be allowed by all users, rather than restricting access to one user at a time

Finally, Morris [89] has suggested a list of design guidelines that can be categorized as relating to regions, clutter reduction, access permissions, group dynamics, work style, and usability. These guidelines were, also, summarised by Kharrufa [71] as follows:

- Regions
  - provide a central area for sharing resources
  - visually distinguish different tabletop regions
  - place user controls on the table edges
  - allow for structuring the space like providing regions for trash
- Clutter reduction
  - consider the use of individual targeted audio as an alternative to visual representations when appropriate
  - provide personal storage areas that can be closed and restored in a fluid manner
- Access permissions
  - provide means for fluidly controlling the access rights of documents
  - make these access rights visible to increase awareness
- Group dynamics
  - provide private and public, audio and visual feedback to increase awareness and regulate participation levels
  - consider the location of controls as this also has an effect on participation
  - enforce a structure on the interaction as this can help users with special needs
  - prevent individual users from executing global level actions that affects others
- Work style
  - provide private audio feedback to help facilitate smooth transitions between tightly and loosely coupled activities
  - provide global controls that can only be executed collaboratively to increase team spirit

- Usability
  - focus on design issues that are related to promoting effective collaboration rather than speed and efficiency

2.2 Collaborative Group Work

As computer systems became more capable, group-oriented software started to see popularity and commercial and academic interest. People tend to work together to accomplish their real life tasks, and computers can play a very important role to facilitate their group working. A computer software that is designed for group work is called a *groupware*. Group working is more complex than that of a single person, it is influenced by the physical environment as well as the social factors, and experimentation in this area is more difficult to control and record (Dix et al. [32]). The support of group work has evolved naturally from a drive to increase personal productivity, and could lead to significant improvements in business efficiency and cost-effectiveness (Olson and Olson [102]).

The group work process, and other more people-oriented aspects which are central to improving group efficiency, can be considered in four categories (Wilson [153]):

1. Individual human characteristics such as conversations patterns
2. Organisational aspects such as the structure and culture of organisations
3. Group work design issues such as user involvement in the work design process
4. Group dynamics aspects such a group decision making and the collaboration process

Wilson [153], also, defined Computer Supported Cooperative Work as: “A generic term that combines the understanding of the way people work in groups with the enabling technologies of computer networking and associated hardware, software, services and techniques.”

Computer Supported Collaborative Work, or simply, *CSCW*, is a very related area of research to group working. It is a research field that involves factors from different disciplines and focuses on tools and techniques to support group working using computer systems (groupware). CSCW provides its users with the ability to collaborate and work together in co-located or distributed settings to accomplish shared goals (Eseryel et al.

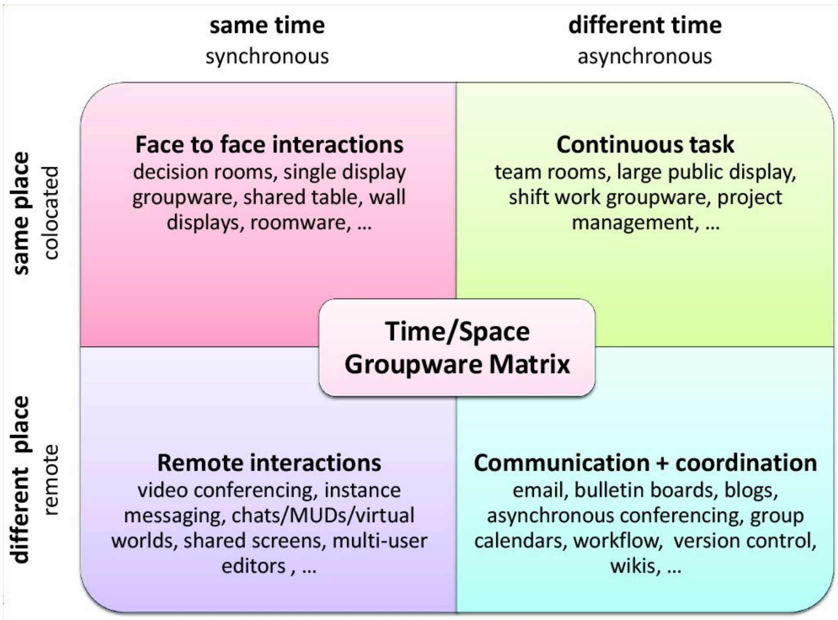


Figure 2.1 – CSCW Matrix

[38]). Collaboration is considered successful when the goal is achieved by the group not an individual. Within CSCW, activities require three elements to be shared effectively: mutual responsiveness, commitment to the shared task, and commitment to mutual support (Bratman [21]). As the aim of CSCW is to support group work effectiveness, it is concerned with the group working process and the technology that might be used to support it (Olson and Olson [102]). CSCW has proven to be beneficial in many situations, however, it introduced some practical challenges. For example, users may simultaneously access shared areas of the screen and change some settings there. Also, the ease of reaching digital artefacts on multi-touch surfaces may affect the efficiency and collaboration level of users (Morris et al. [93]). CSCW and multi-touch tabletops will be discussed later in this review.

Any CSCW system should take into consideration the time and location of interaction. CSCW Matrix (Baecker [9]) is used to conceptualise CSCW systems by considering the context of a system's use. The matrix considers work contexts along the two dimensions of time and space (location). Location determines whether collaboration is co-located or distributed; and time determines whether individuals collaborate synchronously (same time) or asynchronously. This matrix is illustrated in Figure 2.1.

CSCW technology can also be considered in four categories (Wilson [153]):

1. Communication mechanisms enabling people at different locations to see, hear and send messages to each other, for example, video conferencing and electronic mail
2. Shared work space facilities enabling people to view and work on the same electronic space at the same time, for example, remote screen sharing
3. Shared information facilities enabling people to view and work on a shared set of information, for example, multi-user databases
4. Group activity support facilities to augment group work processes, for example, the co-authoring of documents, and idea generation

2.2.1 Cognition in CSCW

Dix et al. [32] described how the group learn to work together and share the knowledge during group work. Dix et al. [32] argument referred to a school of thinking which regards thinking as happening not just within the head, but in the external relationships with things in the world and with other people; this is called distributed cognition (Lave [77] and Hutchins [62]). Traditional views talk about the movement of information between working memory and long-term memory, and it is not so difficult then to regard bits of paper, books and computer systems as extensions to these internal memory systems [32]. Similarly, many models of human cognition regard the mind as a set of interacting subsystems, and hence, the step to regarding several people as involved in joint thinking is not difficult [32].

Distributed cognition has profound effects on the way interface designers look at group working. It emphasizes the importance of mediating representations, for example, the drawings on a shared surface. These representations can be an embodiment of group knowledge in addition to being means of communication. Furthermore, it constantly reminds us that communication is not just about getting knowledge from one person's head to another, but about the creation of new group knowledge. It is not necessary to understand completely the individual's cognitive processing in order to design effective groupware, instead, the focus should be on the analysis of existing group situations and design of groupware on the external representations used by the participants (Dix et al. [32]).

In the interviews conducted on educators and others who regularly view shared-computer, the researchers recognized several drawbacks of present collaborative work practices (Amershi and Morris [6]). For example, the variation in reading speed between different members of the group can make shared computing annoying, such as when drivers scroll too quick or slow, or navigate away from pages earlier than observers have completed reading them. Another example is the lack of awareness when dominating group members can overshadow the attempted contributions of others, leading to reduced awareness of others skills and suggestions [6].

2.2.2 How people work around tabletops

The factors that make collaboration around tabletops effective should be understood in order to design successful groupware applications (Kharrufa [71]). Tang [136] suggested that interface designers should "observe how people collaborate then build software that facilitates collaboration based on those observations, giving the users the "tools" that are "naturally" defined in face-to-face interaction". Researchers, such as Tang [136], found that sharing activities on the table improves the collaborative experience and structuring of the group work, as compared to other settings. Activities around the table and the close proximity allowed for by the large workspace of tables, play a role in focusing attention, drawing collaborators together, aiding in the expression of ideas, promoting a high degree of awareness, improving coordination, and allowing for parallel interaction [71, 136]. Furthermore, it is observed that the spatial orientation among collaborators and the drawing space also played a role in coordination and in defining regions and ownership on the surface.

There are several factors that shall be taken into consideration when observing group work around tables (Kharrufa [71]). Of those, two have the most significant impact: spatial considerations, and communication. Spatial considerations include issues that relate to the tabletop surface area and artefacts on that area. Theses issues include the table size and how the space is divided, as well as the objects location and orientation, and objects ownership and scale. Table space plays an important role in structuring group activities (Scott et al. [119]). Users usually divides the space into three areas: the spaces directly in front of them which is used as personal spaces (Kruger et al. [74]), the space in the middle of the table as a public (group) space for collaborative tasks [74], and the space that is left as a temporary storage space.

Kharrufa [71] showed that "the collaboration around tables is different from collaboration at other devices, mainly because of the unrestricted, face-to-face style of work that tables afford. This style of collaboration leaves open a space for direct human interaction and a greater reliance on verbal and non verbal communication channels." Conversation is the principal means of collaboration. Morris et al. [92, 88] categorised the different types of conversation in collaborative tasks according to whether they are related to the task itself, planning of the work on the task, or needed resources management[71].

2.2.3 Group awareness

Nacenta et al. [99] defined group awareness as the understanding of others presence, locations, and current activities in the shared workspace. A good sense of awareness can help people simplify communication, find opportunities to help one another and coordinate activities and access to shared resources.

Group awareness in tabletop collaboration is maintained through three main mechanisms [99]:

1. Territoriality: is an organizing principle for interaction on tabletops. It is based on the physical reality of the presence of a user and his/her reach as well as the physical extents of the table surface. Groups in general, divide the space of a tabletop into three territories: personal, group, and storage [119, 74]. These different regions give different types of individual and shared activity that requires awareness information interpreted according to the territory in which it occurred
2. Artefact's feed through: is the feedback produced by artefacts when they are manipulated by an interaction technique. Although the feedback is usually intended for the person performing the action, it can also inform others who are watching. In addition, feed through can be manipulated to provide better awareness information. One important type of feed through on tables is artefact orientation [74]. Collaborators use the orientation of objects in real-world tables to determine use and ownership, and to facilitate communication and coordination with others
3. Consequential communication: The information produced by arms as people carry out actions in a workspace is called consequential communication. This is important in tabletop collaboration since it allows people to directly observe the position and movement of hands. The way that an interaction technique carries out an action in the workspace will have an effect on the amount of consequential information that gets transmitted

For awareness to be successful in collaboration scenarios, each collaborator must maintain awareness of what others do. In the case of co-located groupware, the members of the group were physically close to each other, which means they could keep position side by side and be aware of what each other is doing and saying. All of them could see how the task was progressing, and view the information on the display (Rogers and Lindley [112]). However, when collaborators are distributed, awareness is maintained by utilising other techniques. That shall be discussed in the coming subsections.

2.2.4 The role of artefact orientation

The coordination role of orientation is evidence in how the users can set up their personal and shared spaces. While people sit or stand at various positions around a multi-touch tabletop, they will be seeing the contents from various angles. One general answer to this problem is to let the software to reorient objects (artefacts) in order that an individual is able to view them in a correct orientation (Kruger et al. [74]). The coordination role of orientation is evidence in how the people can set up personal and section spaces and how the signal can possess the objects. In the condition of communication, the orientation is helpful in beginning communicative exchanges as well as in long-term talking regarding any specific work that may affect the level of collaboration [74].

To preserve the simplicity of around-the-table interaction while supporting tabletop applications for groups engaged in face-to-face collaborative activities, re-orientation mechanisms can be used that enable interactions with arbitrary artefacts positioning and orientation on a tabletop surface as demonstrated by Shen et al. [122]. The re-orientation mechanism should address the issue of viewing objects at different angles by providing a user-oriented view of the artefacts that other group members are manipulating. However, allowing objects to be freely rotated in order to permit the use of orientation for communicative purposes may cause participants to perform rotations unintentionally, while scaling or moving objects for example, and spend time trying to return artefacts to suitable orientations (Morris et al. [91] and (Kruger et al. [74]).

2.2.5 Tabletop collaboration support

Earlier research in the area of collaborative work focused on adjusting conventional applications interfaces to add collaboration support. Another approach was also proposed that make use of the multi-touch tabletop interfaces powerful collaborative features (Tuddenham et al. [141]). Those studies propose that a tabletop method for collaboration of work activities can assist in overcoming the limits of conventional tools and offer beneficial representations of information layout. The design challenges that are involved in using tabletops include the legibility of the presented information, utilising an efficient navigation mechanism between the different parts of the table surface [17], and supporting awareness among collaborators [141]. The benefit of collaborating around a mutual display is the combined context it gives (Amershi and Morris [7]).

Collaboration is a significant feature of group work which needs a clear support of the groupware. Collaboration is applied in a broad sense, that people, or agents, mutually accomplishing tasks which they could not easily do otherwise. The truly user-centred system should accept and support collaborative interactions among all users (Twidale et al. [142]). The research on collaboration emphasises the level to which awareness of group and individual activity, information sharing, and coordination are essential to successful collaboration. These features are evidently significant concerns in the design of computer systems to support collaborative work (Dourish and Bellotti [33]).

Tabletop interface research has studied interaction with various artefacts, like a desktop of files or digital photographs. The concentration of this task is about interacting with particular files which have been openly and obviously transferred into the tabletop system [8]. Other methods for this approach require the users to shift their files from the personal storage device or laptop computer into the shared area of the tabletop display (Collins [27]). Artefacts and workspace sharing is one of the most general virtual work group activities, and is frequently appear in settings of shared-computer. For instance, a group of students work collectively on documents for homework. Another example of group work on tabletops is the hierarchical compilation of digital artefacts which has been discovered in the "Personal Digital Historian" project [120, 121] as a way of raising the scalability of the tabletop interface. Interaction with huge hierarchies through different types of associations has been also explored, although the evaluation highlighted the overcrowded and cluttered inside the cluster of information as a major trouble in the interface (Shen et al. [124, 121]).

An interesting point to consider when studying group work with multi-touch tabletops is the amount of parallel participation that users engage in during their work. Multi-touch tabletops support concurrent interactions by more than one user, which, generally, should enhance productivity (Basheri et al. [14]). This is an important feature that other means of group work, such as PC based collaboration, do not support as they only provide sequential participation (Hilliges et al. [60]).

Common shared space can be provided in addition to private and local shared spaces together. As described in Subsection 2.2.2, workspace division, known as territoriality, is a useful organizing principle for interaction on tabletops. These different regions result in different types of shared and individual activity, requiring that awareness information be interpreted in light of the territory in which it was produced (Nacenta et al. [99]). This concept of awareness is very important when analysing collaboration with tabletops, and it becomes even more significant when collaboration is considered with remote, or distributed, collaborators. In recent times, virtual team collaboration has gained much popularity for many projects. In an examination of around 204 knowledge workmen, 85% of respondents made statement of having exposed a personal demonstration to other individuals to share the end result of work output (Morris [87]). Sharing a computer that is meant for remote access can be unproductive when collaborators conflict on how to solve problems or follow directions (Tang et al. [134]).

The incorporation of remote partakers with the co-located collaboration activities is achievable and the demand of a tabletop environment for those remote users is of huge worth, particularly in creative responsibilities such as brainstorming or common discussions with the involvement of some kind of media. Desktop computers may reduce the group communication, although they possibly allow access to data and efficiency tools applicable to the task in the hand. When people work together in a co-located setting, they frequently use devices such as paper, pencils, pens, and printouts, then work over table or some kind of supporting surface. They share and contribute to the information located on this table, use objects on the surface, and expand thoughts and work products (Kruger et al. [74] and Tuddenham et al. [141]). However, in the distributed settings, the groupware must provide alternative for face-to-face communication and digital artefacts organisation, as well as an awareness maintenance mechanism.

2.2.5.1 Collaboration styles

As people work together in a group work task, they adopt different collaboration styles. Sometimes, they work on the same problem; at other times, they may separate to work on different problems. These different styles allow them to investigate solutions, test ideas, and plan their work. Isenberg et al. [64] identified eight styles of collaboration that users around tabletops may follow during their group work (these styles are described below). They also categorised those styles into two categories: *close* collaboration and *loose* collaboration. Generally, it is found that participants spend almost half of their time in close collaboration during the given task. Close collaboration is usually encouraged, hence systems should facilitate its styles as much as possible [13].

Collaboration styles are coded by Isenberg et al. [64] in order to understand which information and views of the workspace users may share and collaborate on at a given moment. The styles are coded based on the users data views and personal interactions. The following are the collaboration styles as described by Isenberg et al. [64]; Figure 2.2 illustrates the styles with their degree of collaboration coupling.

DISC: Active **DISC**ussion about the data or task. Limited system interaction (e. g., pointing to items or scrolling in documents)

VE: **V**iew **E**ngaged. One person is actively working; the other watches and engages in conversation and comments on the observed activities, but not interacting with the system

SV: Sharing of the **S**ame **V**iew of an artefact or data view. For instance, users either look at the same document or the same search result list together at the same time

SIDV: Sharing of the **S**ame **I**nformation but using **D**ifferent **V**iews of the data. Users, for example, read the same document but using their own copies (views) of the document

SSP: Work is shared to solve the **S**ame **S**pecific **P**roblem. Both users use different artefacts from a shared set. For example, they query the system for some data results, then divided the work and each person read one half of the results

SGP: Work on the **S**ame **G**eneral **P**roblem but from different starting points. For example, both users search the sets of available artefacts to find information about something but start from different searches and consider different sets of artefacts

DP: Work on **D**ifferent **P**roblems, and hence different aspects of the task. For example, one person is interested in searching for information about a certain topic, while the other searches for events around a totally different topic

D: **D**isengaged. One person is actively working, the other is watching passively or is fully disengaged from the task

To study and analyse collaboration styles, experimental sessions of the users who participate in a study are usually video recorded then analysed using video time-line analysis methods and tools [64, 4]. As mentioned previously, these styles are grouped

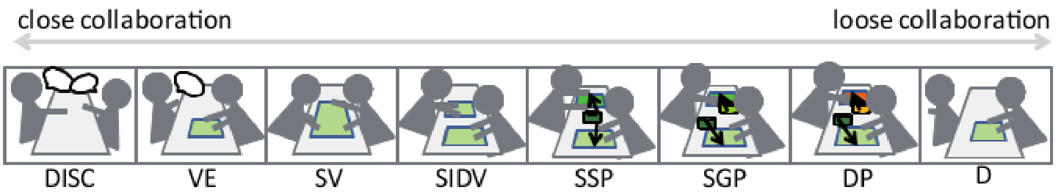


Figure 2.2 – Collaboration styles and coupling as identified by Isenberg

into two categories: close collaboration and loose collaboration. The first five styles are considered close styles of collaboration, while the last three are considered loose styles. Sharing of information and discussion of ideas are the most noticed characteristics of close collaboration phases. During phases of loose collaboration, explicit verbal sharing of information and discussion of ideas is less frequent as team members were looking at less related information and were, generally, working in parallel [64]. How much information users share and how frequently they communicate with each other have an influence on how well teams are able to connect the facts and progress through the task [64].

2.2.6 Effects of users distribution

Olson and Olson [101, 104, 103] have studied the effects of users distribution on the collaborative work and groupware. Their findings fall into two categories: behaviour that will change for the better when the technology achieves certain qualities, and behaviour that will *never* change which confirms that distance will continue to matter even with significant technological advances [101]. They identified four concepts to be used to analyse the group work:

1. Common ground
2. Coupling of work
3. Collaboration readiness
4. Collaboration technology readiness

Common ground is a characteristic of the users, and it refers to the assumption that collaborators have some level of common knowledge (Olson and Olson [101]). Moreover, the collaborators are aware that they have this knowledge in common. However, the principle of common ground is not just as simple as that, it is formed through specific knowledge from the person's appearance and behaviour during the collaboration and interaction. It is found that distributed users face difficulty of establishing common ground. One of the main reasons of this difficulty is the missing of user's awareness of the state of each other, both their presence–absence and their mental state. This awareness is an important part of common ground. Olson and Olson [101] found that "the more common ground people can establish, the easier the communication, the greater the productivity." That applies for both, co-located and distributed settings. And to enhance the situation in the distributed settings, let the users get acquainted and talk with each other over video-conferencing for instance, or even by meeting in person if feasible.

Coupling of work is a characteristic of the work itself. This concept is used to refer to the extent and kind of communication required by the task, and the decomposability of the task [101]. When the work is tightly coupled, that means it strongly depends on the talents of collections of workers and is non-routine, and its components are highly interdependent. This kind of work typically requires frequent, complex communication among the group members, with short feedback loops and multiple streams of information. In contrast, loosely coupled work has fewer dependencies or is more routine [101]. Tightly coupled work is very difficult to do remotely in distributed settings because it needs rapid communication channels with support of high level of awareness and repair of ambiguity. To enhance the remote collaboration from the work perspective, Olson and Olson [101] suggest that tasks should be designed to be loosely coupled and needs simple communication.

Collaboration readiness refers to the fact that not all users (or communities) are ready to collaborate remotely. Some users are used to collaborate in their work, which makes the transition to the distributed settings a smooth step. Others, may not find collaboration, in general, a welcomed way of work, and will find the remote settings a more awkward experience, which will severely affect the group performance as a whole. Olson and Olson [101] suggests that groupware and remote technologies should not be introduced immediately to communities that do not have a culture of sharing and collaboration.

Collaboration technology readiness refers to that some users (or communities) cannot quickly adopt new advanced technology that support remote groupware. Putting the users in a situation where they have to use an advanced groupware for remote collaboration that they are not used to may negatively affect their experience and performance. Advanced technologies should be introduced in small steps (Olson and Olson [101]).

2.2.6.1 Collaboration with distributed remote tabletops

The possibility of linking two or more geographically-separated tabletops has been investigated to provide a shared workspace for remote distributed collaborators. Each of those distributed collaborators sits at their own tabletop display. The displays are then linked so that the remote collaborators all see the same artefacts and can then interact simultaneously and see each others' actions, as if they are around a co-located tabletop (Tuddenham et al. [140]).

When used in a co-located configuration, tabletop interfaces are a form of single display groupware that use a large display together with multi-user direct input mechanisms such as styluses or a multi-touch surface [140]. Some systems took inspiration both from work on augmented paper (Wellner [149]), and studies of co-located tabletop collaboration (Streitz et al. [130] and Tang [136]). Another aspect that has been taken into consideration in recent research is the study of human behaviour around tabletops (Kruger et al. [74] and Ryall et al. [116]).

Supporting remote collaboration had tended to use conventional monitor/mouse interaction to present shared workspaces. However, problems have been encountered with such experiments. For instance, on a conventional monitor there is often insufficient space for collaborators to work in different parts of the workspace without losing an awareness of each others' actions (Dourish et al. [33] and Gutwin et al. [51]). Another problem of these solutions is the lack of awareness among collaborators about each others' actions in the workspace, with collaboration suffering as a result. The problem is particularly acute in systems in which each collaborator can manipulate their view of the workspace independently of others, for example to scroll to a different region of the workspace (Tuddenham et al. [140] and Gutwin et al. [52]).

Such problems can be overcome so that remote collaboration becomes, generally, effective as co-located tabletop collaboration when using, relatively, large displays of tabletop with their interaction techniques [140]. In large-format remote collaboration systems, each remote collaborator uses their own large display with direct input mechanisms such as styli or touch. The tables are then linked together to provide a shared workspace for remote collaboration. An example of such systems is VideoWhiteboard (Tang and Minneman [135]) where remote collaborators could interact simultaneously to draw some sketches with the shadows of their arms and bodies were projected on the remote part of the shared workspace to maintain awareness and a sense of presence. Another example is

Clearboard (Ishii and Kobayashi [65]) which allow collaborators to even make eye contact through the drawing surface. This has led to projects that use purely digital artefacts to investigate large format displays for remote collaboration for different kinds of tasks and human factors effects. They present each remote collaborator with a shared workspace that contains interactive digital artefacts on a large tabletop display [132, 140]. Human factors and remote embodiments in mixed-presence collaboration have been investigated in several researches such as VideoArms (Tang et al. [133]).

Tuddenham and Robinson [140] put three questions that a researcher should take into consideration when studying the field of remote tabletop collaboration:

- Why might tabletop interaction, so effective for co-located collaborators, also be effective for remote and mixed-presence collaboration?
- Which elements of co-located tabletop collaboration are important for remote and mixed-presence tabletop collaboration?
- What additional factors must be considered in the design of tabletop systems for mixed-presence collaboration, as opposed to just remote collaboration?

There are general characteristics of co-located tabletop collaboration that should be presented in remote tabletop collaboration system to get a similar experience. These characteristics were specified by Tuddenham and Robinson [140] and also described by Scott et al. [118]:

- A large horizontal display surface
- Collaborators can sit in different positions around the edge of the surface
- Direct input mechanisms (stylus or touch)
- Digital artefacts can be moved and reoriented using a technique such as Rotate'N'Translate (Kruger et al. [75])
- Simultaneous interaction by multiple collaborators
- Collaborators are aware of each other activity
- Collaborators can communicate with each other

However, it is very important for tabletop groupware designers to keep in mind that, as described by Olson and Olson [101], it is impossible to make remote collaboration exactly the same as co-located collaboration because of many factors presented in Subsection 2.2.6.

2.2.7 Computer games

The group task that is selected for this research is a multi-player computer game that needs a group of users to work in it together to achieve game goal. Computer games can be defined as an activity which involves goals, rules, and competition. Dempsey et al. [30] defined a computer game as "a set of activities involving one or more players. It has goals, constraints, pay-off, and consequences. A game is rule-guided and artificial in some respects. It involves some aspect of competition, even if that competition is with oneself". Prensky [108] listed the main elements that a software must have in order to be classified as a computer game. These elements are:

1. Rules: are the directions and restrictions that must be followed and accepted by the game player in order to achieve the goals of the game. Rules are important to games because they put the game player in a defined frame of work, which means that the game player must take specific paths to reach certain goals and will ensure that all of the game players are playing on an equal ground
2. Goals or objectives: are what the game player needs to achieve in order to meet the requirements of the game, i.e. win the game. The goals could be a sort of milestones (sub-goals) towards the main final goal, to collect more points, to win extra lives, and so on. In a game, achieving the goals is what *motivates* the game player to play
3. Outcomes and feedback: are how game players measure their progress against the goals. The basic outcomes of a game are either win or lose. Feedback, on the other hand, occurs when something in the game changes in response to what the game player does. Feedback will give the game player information about whether the action taken is positive or negative, whether the game players are staying within or breaking the rules, and whether the game players are moving closer to their goal or not
4. Conflict, competition, challenge, and opposition: are the elements that provide problems in a game that the game players are trying to solve. The problems might consist of fighting opponents, a puzzle or anything that stands in the way of the game player's progress
5. Interaction: is an important element of computer games, and it can be categorised into two groups: interaction between the players and the computer, and interaction between the game players themselves. The more intuitive and easy the interaction,

the better user experience the players will have, which is a key factor in game success

6. Representation: means that the game is about something, i.e. the theme of the game. A game can be about solving a puzzle, pattern recognition, conflict resolution, racing against time, and so on.

Games are fun, challenging, an interactive social experience that can be shared with friends and family, and they provide a lot of entertainment. There are several reasons that make computer games a very interesting application to study group work. Below are some of these reasons as described by Garris et al. [45] and Oblinger [100]:

1. There are major shifts from traditional to learner-centred modes of instruction. This is supported by the availability of new technologies in an educational setting, i.e. the integration of multimedia and interactivity in computer-based learning
2. The ability of computer games to enhance the understanding of complex subject matter
3. The ability of computer games to increase the level of involvement and engagement among game players
4. The ability to offer a powerful learning environment, such as allowing learners to immerse themselves within RBI[5] environments
5. Create strategies for overcoming obstacles
6. Understand a complex system through experimentation
7. Games enhance user motivation which could lead to greater attention and retention

2.2.7.1 What can games teach us about HCI and Collaboration?

The fields of Human-Computer Interaction and computer games can greatly enrich each other (Jørgensen [69]). Games can benefit from the HCI evaluation methods, while HCI can utilise the interaction techniques and supporting user communication from games. A generic feature of the two fields is the dedication to providing the users with what they want.

One of the most interesting features that HCI can take from game is the fluid system-human interaction; games communicate information to users in ways that do not demand the users' attention and do not interrupt the flow of work (Dyck et al. [34]). For example,

[5] RBI: Reality Based Interaction (see Subsection 2.1.3).

replacing non-critical message dialogues with calm messages would not steal focus from the user's active window. Another feature is by making interface elements attention-aware which would result in fewer actions like resizing, opening, closing, minimizing, and maximizing windows [34]. Attention-aware elements are user interface elements that automatically modify themselves based on the amount of attention users are paying to them. This technique is effective at reducing visual clutter in areas of non-interest and increases the size of the usable workspace [34].

In the collaboration side, Manninen [81] described the great potential of multi-player games towards collaborative work research by stating "Multi-player games offer enormous potential for collaborative activities and shared experiences. With the enhanced communicative features, the players would be able to express themselves and share their thoughts more naturally. Furthermore, the rich interaction support would offer players a more flexible and creative set of actions." When the rich interaction forms in multi-player game sessions were analysed, the results indicated that the users can effectively use various forms of communication, which is a crucial part of collaboration (Morris et al. [92, 88]). A creative combination of various communication channels makes it possible to enhance the overall interaction and further increases the communicative, collaborative and constructive uses of the system [81].

2.2.7.2 Games and multi-touch tabletops

Studies have shown that the majority of computer game players prefer to play in a cooperative manner (Goh et al. [46]). Such studies have also shown that players would favour cooperative style games more if they were engaging one another on shared interactive surfaces instead of gaming consoles [46]. That gives a clear clue that multi-touch tabletops have a great potential in this regard (Anstead et al. [8]). There have been many interesting games designed on multi-touch tabletops that have demonstrated good potential for collaborative play [46]. For example, parallelism of interaction afforded by multi-touch interaction is a powerful factor facilitating collaboration. Also, division of labour occurs naturally among the team members who collaborated efficiently to get the overall task done [116]. Another important factor is the physical proximity of acting together on a shared surface which seems to enhance this form of collaboration [46].

Goh et al. [46] have suggested the following general design guidelines for multi-touch tables games in order to have an effective collaborative environment:

- Use physical space and territoriality when locating user-specific touch points
- Use multiple (preferably greater than 2 touches) spatially distributed co-touch points to implement enforced collaboration
- Use co-touch points to remove the availability of an item or event that is desirable to all parties
- Use sub-goals whose fast realisation requires simultaneous correct action combination by all players but a slower realisation if only a partial solution is provided by a subset of players
- Use recognisable sound cues to prime impending collaborative activity

However, Goh et al. [46] mentioned that although these guidelines (or design patterns) can be generalisable, but they have to be validated when they are used in designing and building different multi-touch tables groupware.

2.3 Chapter Summary

In this chapter, previous research that have been done on the topics related to this thesis were reviewed. The review was concerned with two main areas: Human-Computer Interaction (Section 2.1) and Collaborative Group Work (Section 2.2). Within the human-computer interaction area, the review presented how user interface evolved until it reached the multi-touch surfaces. It also reviewed the interaction styles and the reality based interaction framework. Then it gave an overview of the usability analysis for groupware, and finally it introduced the background of multi-touch tabletops technology and their groupware design guidelines as proposed by some researchers. As for the collaborative group work area, the review presented the most important topics that affect the CSCW field, such as cognition, practices around tables, and group awareness. It also put the multi-touch tabletops with the context of group collaborative work and how they can help in maintaining close collaboration styles between users. This section has also presented the effects of user distribution on usability and collaboration. The it concluded by an overview of computer games and their role in HCI development and collaborative work analysis.

This review should form the basis of the topics discussed in this thesis, and will be used as guidelines for the research and experimental design that help evaluating the hypothesis of collaborative work by using distributed tabletops. The work presented in this research should focus on answering the problems of enhancing collaborators awareness of multi-touch tabletops in distributed environment and the usability of such systems.

3 Method

In this chapter, the methodology adopted for this research is presented. It includes a discussion of the study design, analysis approaches and techniques, and the data sources used. The analysis procedure is explained to show how the research questions introduced in the beginning of this research are going to be answered. Finally, this chapter shall also present the experimental design which was employed to build the environment and the software application that were used during the experiment sessions with participants.

The evaluation method used in this thesis is based on conducting a controlled experiment through which participants used the developed software application to carry out a carefully designed task that satisfies the requirements of the hypothesis testing by assessing the outcomes. The method used in assessment process is a comparative analysis in general. As the experiment is executed in two conditions (or scenarios), co-located and distributed, the outcomes of each condition is firstly analysed alone, then compared against the other condition.

3.1 Study Design

This research is a quantitative study based on an experiment that is designed specifically to answer the research questions proposed in the beginning of this research in Section 1.4.1. Ross and Morrison [115] mentioned that experiments are designed to "test hypotheses regarding causation, for example, that a particular instructional strategy leads to better student performance." For this research, the experiment should serve as the instrument to test the significance of differences in the HCI aspects between the two scenarios: co-located where participants are using the same table, and distributed where participants are using two physically separate tables. These two scenarios are illustrated in Figures 3.1 and 3.2.

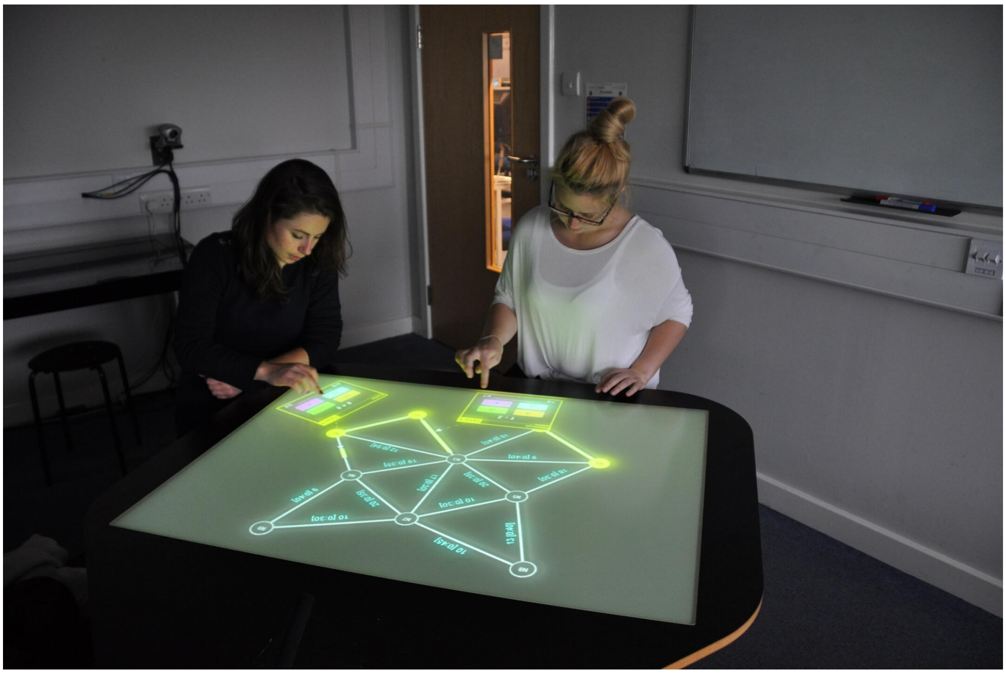


Figure 3.1 – *Co-located* scenario (same table)

Figure 3.2 – *Distributed* scenario (two separate tables)

The following points should be taken into consideration when designing a scientific experiment, as mentioned by Field [42]:

- The proposed outcomes of the experiment: what are the variables that changed when the experiment has been executed? These are the *dependent variables*
- The proposed causes of the outcomes: what are the variables that caused the *effect* to change the outcomes when the experiment has been executed? These are the *independent variables*
- Causal relationship between causes and effects: how the link between independent and dependent variables is formed and what are its attributes? This is the key to answering the research questions (see Section 3.4)

Several techniques are used to design experiments. The two most common techniques are the *Between-Group* and *Within-Subjects* designs [42, 78]. A briefing of these two techniques is presented in the following subsection with justification of why one is picked over the other for the purpose of this research.

3.1.1 Overview of design techniques

To collect data from an experiment for the purpose of analysis, two methods (or techniques) can be used, *between-group* and *within-subject*s. It is important to design the experimental scenarios in a way that suits how the resulted data is going to be collected; the way the data is collected determines the type of test used to analyse the data later (Lazar et al. [78]). The introduction of variation to the experimental conditions differs depending on the data collection method that is used. In *between-groups* design, differences between conditions can be caused by the manipulation that was carried out on the participants, and the differences between the characteristics of the people allocated to each of the groups. While in *within-subjects* design, differences can be caused by *mainly* the manipulation that was carried out on the participants, in addition to any other factor that might affect the way in which a person perform from one condition to the next. That is why it is important to carefully design the experimental procedure to reduce the systematic confounding effects such as fatigue and boredom between conditions (Field and Hole [42]).

3.1.1.1 Between-group design

Between-group design, also known as *independent measures*, is an experiment that has two or more groups of subjects each being tested by one and only one condition of the study, so every participant is used only once. In other words, the independent variables are manipulated using different participants (Lazar et al. [78]).

The advantages of this design:

- Simplicity
- Less chance of practice and fatigue differences
- Useful when it is impossible for an individual to participate in all experimental conditions

But it it suffers form some practical disadvantages:

- Expensive in terms of time, effort, and number of participant
- Insensitivity to experimental manipulations

One of the major concerns of this design is that differences between the participants themselves may cause undesirable systematic effects of confounding variables. It is more than likely that participants will differ in many respects such as their IQ and mood. These variables contribute to the variation between conditions, which will affect the sensitivity of the carried out tests (Field and Hole [42]). To minimise this effect, participants are allocated randomly to experiment conditions; this should ensure that these confounding variables are evenly distributed across conditions.

3.1.1.2 Within-subjects design

Within-subjects design, also known as *repeated measures*, uses the same subjects with every condition of the study. It manipulates the independent variable using the same participants in every different experiment condition; each participant is exposed to all conditions then the outcomes are analysed to test for variance. This design is usually recommended unless it is impossible to use (Field and Hole [42]).

Advantages of this design include:

- Needs fewer people, as each participant is used several times in all the experimental conditions
- More sensitive because there are fewer sources of random variation to obscure the effects of manipulations of the independent variables

Two important disadvantages are known for this design:

- Carry-over effect from one condition to another
- The need for conditions to be reversible; that is, being in one condition does not have irreversible effects that prevent the participant being used in another condition

This design technique is chosen for this research because of the advantages mentioned. As shown later in Subsection 3.3.1, the sample used in the experiment consists of 32 participants who were exposed to the two conditions of the study. It would have been very difficult to double this number if the first design, *within-group*, is used because of the time constraints. Lazar et al. [78], recommended this deign as it enhances the results accuracy in the field of HCI research, and it is more natural to see participants engaged in more than one condition as in real life, which will enrich the observational side of the analysis.

To overcome the disadvantages of this design, randomisation and counterbalancing the order of the different conditions can be used (Field [42]). It is very important to keep the other sources of systematic variation to a minimum to increase the sensitivity of experimental manipulation using only the variations that the researcher introduces and control [35]. To achieve this, *randomisation* of participants to experiment conditions is used; that is, the list of participants names is randomly assigned to the conditions and the participants know in which condition they will begin only when they start the experimental session. By this, it is ensured that any differences within the groups are not systematic and that any differences are due to chance. In within-subject design, the two most important sources of systematic variation are *practice* and *boredom* effects. These effects are impossible to eliminate completely, but can be reduced to ensure they produce minimal systematic variation between the conditions by *counterbalancing* the order in which a person participates in a condition. This is done by randomisation of conditions, that is, randomise to determine in which order the conditions are completed [42, 35]. This is easily applicable in this research as the two conditions are reversible and the order does not have effects on the conditions themselves.

It has been noticed in within-subject design that the effect of manipulation is much more apparent than the between-groups. It can be concluded that, other things being equal, within-subject designs have more power to detect effects than between-groups design (Field [42]).

3.1.2 Variables

As mentioned previously, changes are introduced to independent variables (*conditions*) in order to study the *variation* on the dependent variables[1] (*outcomes*). There are always two sources of variation as explained by Field and Hole [42]:

1. *Systematic variation*: where the experimenter is altering an aspect of the experiment to all of the participants in one condition but not in the other condition. This is important kind of variation as it is controlled and can be studied directly.
2. *Unsystematic variation*: which is random factors that exist between the experimental conditions, such as participant's IQ, time of day, differences in ability, etc. This kind of variation is best be eliminated, though it is not always possible, as it is not easy to control nor to see its effects.

The two types of variables (independent and dependent) used through this research were based on the common variables found in HCI studies (Lazar et al. [78]). The essential independent variable used in this research is the *scenario* (or *condition*), which has two states: *co-located* and *distributed*. The whole thesis is build on the hypothesis that the change of this variable should have minimum effects on the other *dependent* variables.

Dependent variables used in this thesis are categorised into three groups that are mapped to the three areas of the research: Performance, Collaboration, and Usability. Below, is a listing of these variables; they are fully described and analysed in Chapter 5, where they are put in context within the analysis framework.

1. Performance
    a) *Efficiency*
        i. *Duration*: Total time that a group spent on the task (from start to finish/game over)

[1] The outcomes variables are called *sub-factors* in Chapter 5.

   ii. *Effort*: Total number of questions a group has solved during the game (including correct and wrong answers)
   iii. *Speed*: Number of correctly answered questions per minute (the answers that cause progress)

b) *Accuracy*
   i. *Incorrectness ratio*: Ratio of incorrect answers to the total answers a group has given, per minute
   ii. *Added difficulty ratio*: Ratio of the added parts to the game solution to the most efficient solution, per minute
   iii. *Unnecessary work ratio*: Ratio of the time spent on working on irrelevant parts of the game solution to the total time spent on the game, per minute

2. Collaboration

a) *Styles*
   i. *CH*: When the participants are communicating to assist each other
   ii. *VE*: When one of the participants is not actively working on the task but he/she is engaged in watching what the other participant is doing
   iii. *SSP*: When both participants are working at the same time on the same link
   iv. *SGP*: When both participants are working at the same time on the task but on different links

b) *Communication*
   i. *Frequency*: Number of total communication attempts (initiation, responding, and others) per minute
   ii. *Start*: Time of the first communication attempt as a ratio of the total game duration
   iii. *Interval*: Time span from first communication attempt to the last one as a ratio to total game duration
   iv. *Help initiation*: Number of communication attempts for help (ask and offer) per minute during communication interval
   v. *Help response*: Number of responses received for help initiation (affirmative and negative) per minute during communication interval
   vi. *Response time*: Average response time (in seconds) between the participants when they communicate for help

c) *Balance*

   i. *Work*: Total number of solved questions (correct and incorrect) per minute
   ii. *Communication*: Total number of communication attempts per minute

3. Usability
   a) *Satisfaction*: User subjective satisfaction with the interaction experience
   b) *Ease of learn and use*: How easily the user can learn to interact with the new system and to complete the given task
   c) *Physical and cognitive demand*: The level of physical or cognitive requirements that the system exerts on users

The research questions presented in the introduction (Subsection 1.4.1) were proposed based on the effects that the independent variable (*scenario*) may have on the dependent variables. For example, to answer the question of whether distribution has any effect on the user's performance area (research question 1), it is necessary to find out the effects on the sub-components of performance, that is, the variables that contribute to the performance area.

3.2 Data Analysis Approaches

The statistical tests used to generate the results in Chapter 5 are described in this section. Also, an analysis framework is developed to show the step by step statistical procedures that have been used for each investigation with their results (Section 3.5). Parametric tests are the most used statistical tests in data analysis; however, these tests assume normal distribution of data and homogeneity of variances [41]. While some studies in statistical analysis show that the consequence of such violations of these assumptions is less severe than previously thought (Hill and Lewicki [59]), analysis of data in this research will follow the assumptions being met. Therefore, tests for normality and homogeneity of variances are carried out on the data to determine the appropriate statistical tests to use. In case the assumptions are not met, data transformation or non-parametric tests can be considered.

There are certain methods used to assess these assumptions as explained in the following sub-sections. All variables used in this research were checked for normality and homogeneity of variances; the majority of them were found holding the assumptions. Very few variables were found *marginally* not normal or have variances inequality; but that should not affect the accuracy and significance of results (Hill and Lewicki [59]).

3.2.1 Null hypothesis

Each hypothesis presented in this research is presented as null hypothesis and tested statistically to find out whether it can be rejected or not. For each statistical test used, the result should have the following components:

p-value: The probability of observing a test statistic as extreme as (or more extreme than) the one actually observed, which makes the test result significant. The smaller the p-value, the more strongly the test rejects the null hypothesis, that is, the hypothesis being tested. The most common level for the p-value used in statistical tests is 0.05. Hence, when the test p-value is less than or equal 0.05, the hypothesis is rejected; otherwise, the test is said to "*fail to reject*" the hypothesis.

Confidence Interval: The range of values around the statistical test result that are believed to contain, with a certain probability, the true value of that test. A common interval used in statistical test is the 95% confidence interval.

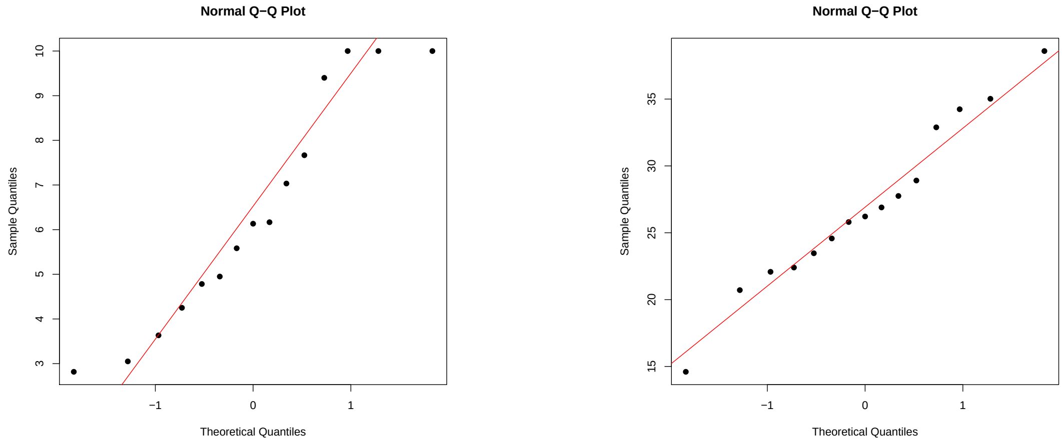
3.2.2 Parametric tests assumptions

As previously mentioned, it is highly recommended that some assumptions must be met in order to use parametric statistical tests. Assessing these assumptions is presented in this subsection.

3.2.2.1 Testing for normality of data distribution

This assumption means that the data points of a variable should represent a sample that is withdrawn from a normally distributed population [41]. Two ways are commonly used to test for normality, visual and statistical; and they should support each other to present a strong evidence of normal distribution.

The visual method depends on plotting the data in concern using a Q-Q chart. The actual data will be drawn as points against a straight line that represents the theoretical



(a) Duration **(b)** Speed

Figure 3.3 – Visually checking normality using Q-Q plots

normally distributed data. The closer the actual data points to the theoretical line the more normally distributed is the data, and vice versa. Examples of two of the variables (duration and speed) used in this research are illustrated in Figure 3.3.

Statistical method to test distribution normality utilises the *Lilliefors normality test* (also known as Kolmogorov-Smirnov test). This test is widely used and can produce strong evidence of normality that can support the visual check (Thode [139]). As other tests, Lilliefors test produces a statistical result accompanied by significance level (p-value). If the results is significant (p-value ≤ 0.05), that means the data is not normally distributed, otherwise (p-value > 0.05) the data is normally distributed.

Applying this test on the two variables that were checked visually, duration and speed, show a non-significant results for both (p-value > 0.05), therefore, their distribution can be assumed normal.

3.2.2.2 Testing for homogeneity of variances

The second assumption is that the variances between data points are homogeneous (or equal). To assess this assumption, a well known statistical test is used; the *Levene's test* (Fox [44]). This test generates a significance level that can be used to verify the equality of variances. If the result is significant (p-value ≤ 0.05), that means that there is inequality of variances and the assumption has been violated, otherwise (p-value > 0.05) the assumption is met.

3.2.3 Paired-samples t-test

The paired-samples t-test is a parametric test that is used when the experiment is designed to look for differences between two conditions with only one independent variable[2], and the same group of participants is involved in both conditions. This test compares two means of dependent variables in the two different experimental conditions, e.g. the participants communication frequency in the two scenarios, co-located and distributed. This test produces the t-statistic (in the form of $t(n) = x$, where n is the degrees of freedom, or number of readings -1, and x is the statistical difference between the means) and p-value which determines if the difference between the two means is significant (if p-value is less than or equal 0.05, the difference is said to be significant, otherwise, it is insignificant). Paired-samples t-test is the main statistical test used in this thesis to assess the hypotheses of differences between the two experimental conditions, as it is widely adopted to compare two means of variables in two experimental conditions [114].

3.2.4 Correlation

Pearson's Correlation Coefficient is the analysis of the relationship strength among different variables in the observed data set. Correlation coefficient, r, falls in the range between -1 and +1, where 0 means no correlation at all. Field et al. [42] suggests to interpret the value of coefficient as follows:

Weak: from 0 to ± 0.3
Moderate: from ± 0.31 to ± 0.5
Strong: from ± 0.51 to ± 1

It is very important to clarify that correlation does NOT imply causality. Correlation shows that there is a relationship between variables, but there is nothing in correlation that tells in which direction between the variables is that relationship. That is, there is no direction of *causality*.

[2] See Subsection 3.1.2 for more details on independent and dependent variables.

Another important point to consider is that there could be a strong correlation between two variables, but statistically insignificant. Only the significant results are taken into consideration in this research. In correlation tests, the null hypothesis states that there is no correlation between the given variables, that is $r = 0$. A *p-value* that is larger than *0.05* means that the correlation is statistically insignificant, which means that the null hypothesis cannot be rejected, that is, the correlation is statistically insignificant.

Another correlation interpretation that is used in this research is the *coefficient of determination (R^2)* matrix [41]. R^2 is interpreted as the variability shared between the variables (as ratios). For example, when the coefficient of determination between two variables is 0.36, that means that the correlation can explain 36% of the variability shared between those two variables. Squaring correlations and transforming r-coefficient to percentage is common in statistical analysis to have an easy to understand meaning and evaluation of correlation.

Finally, to compare two correlation coefficients, as in the case of co-located and distributed conditions, Fisher's z-Transformation test is used in this research [26, 41]. The null hypothesis for this test states that there is no significant difference between the two given correlation coefficients.

3.2.5 Gini coefficient

Gini Coefficient[3] technique is used in this research to analyse the contribution balance between the participants in each group [14]. Harris [56] described the Gini coefficient as it sums the deviation from equal participation for all members of a group, normalized by the maximum possible value of this deviation. Gini coefficient falls in the range between 0 and 1, where 0 means the contribution is perfectly balanced between both participants, and 1 means extreme imbalance.

3.3 Data Sources

In this section, the data sources that were used in for this research are described with detailed explanation on how this data has been gathered, prepared, and cleaned. A

[3] Also called Gini Index.

Scenario	Group ID							
Co-located → Distributed:	1	3	5	7	9	11	13	15
Distributed → Co-located:	2	4	6	8	10	12	14	16

Table 3.1 – Groups and scenarios

demographic summary of the participants who attended the experiment sessions is also presented.

3.3.1 Participants

Initially, the number of participants in the sample was 32, but after cleaning the data as described in Subsection 3.3.3, the total number of participants became 30 persons, divided into 15 groups. Eight of the groups performed the experiment by starting on the co-located condition, then moved to the distributed one; and the other seven groups did just the opposite as shown in Table 3.1. Refer to Subsection 3.1.1.2 for the reason why do the groups switch the experiment conditions.

All the participants were volunteers from Durham University. Some basic information about the participants is given below, and Table 3.2 maps it to groups and members (**M1**: participant 1, **M2**: participant 2).

- **Gender**: 15 females (F), and 15 males (M)
- **Education level**: 4 undergraduate (UG), and 26 postgraduates (PG)
- **Age**: 9 in the range of 21 to 25 years, 10 in 26 to 30, 5 in 31 to 35, 5 in 36 to 40, and 1 in 41 to 45
- **Acquaintance**: members of ten of the groups have not met before the experiment (N), and members of the other five groups were already friends (Y)

3.3.2 Data preparation

For this study, three sources of data were used: questionnaires, system logs, and video recordings. The questionnaires are used to analyse and compare the USABILITY of the system in both scenarios: co-located and distributed. System logs and videos are used to

	Gender		Education		Age		Acquaintance
Group ID	**M1**	**M2**	**M1**	**M2**	**M1**	**M1**	
1	M	F	PG	UG	27	38	Y
2	M	M	PG	PG	34	38	N
3	F	F	PG	PG	25	27	Y
4	M	M	PG	PG	30	37	N
5	M	M	PG	PG	33	43	N
6	F	F	PG	PG	26	27	N
7	M	F	PG	PG	33	30	N
8	F	M	PG	PG	24	22	Y
9	F	M	UG	PG	21	36	N
10	M	M	PG	PG	35	23	Y
11	M	F	PG	PG	30	23	N
12	F	M	PG	PG	23	25	N
13	F	F	PG	PG	28	30	N
14	F	M	PG	PG	26	32	N
15	M	M	PG	PG	38	31	Y
16	F	F	UG	UG	21	23	Y

Table 3.2 – Mapping basic information to groups and members

analyse the PERFORMANCE and COLLABORATION; that should be carried out on both scenarios as well.

3.3.2.1 Extracting data from questionnaires

Each participant was requested to fill in two questionnaires, one for each condition, during the experimental session. The questionnaires for co-located and distributed scenarios are very similar (see Appendix B) with some differences in questions ordering, and phrasing to avoid thoughtless answering. Each questionnaire has a set of general questions about the participant's experience with the system, and another set of questions specific to the scenario. In addition to the task related questions, the questionnaires were used to collect some other information such as gender, age, and education level.

Likert scales are used in this research to collect usability data by questionnaires that were filled by the participants during the experiment sessions. All questions in the questionnaires were designed to have only one of four answers: *Strongly Agree, Agree, Disagree, and Strongly Disagree.* These answers are numbered *1, 2, 3*, and *4* respectively to aid in generating frequency tables that are used in descriptive statistics, then summed up (as suggested in Lazar et al. [78]) to be used in other inferential tests. Questionnaires and their results can be found in Appendix A and Appendix B.

The result for each individual question is presented in Appendix A. However, for the purpose of this research, questions were grouped into categories related to the area to be analysed. That is explained in more details in Section 5.4.

3.3.2.2 Extracting data from system logs

System logs are the main source of data in this research. The application was designed and implemented to log every interaction between the users and the system or between the users themselves (see Subsection 4.2.2). Each session has two logs, one for each scenario. Entries are time stamped, and where applicable, the name of the participant who initiated the interaction is logged as well. Interaction entries are coded to categorise them later in the extraction process.

To make extracting the data from logs easier, some programs were written to check for patterns and entries of interest, then to output the desired results. However, some data was very difficult to extract automatically, so it was extracted manually by reading the logs and looking for the required data. Appendix C presents a sample of a system log.

3.3.2.3 Extracting data from video recordings

All sessions are video recorded in both scenarios as demonstrated in Figure 3.5. The data extracted from videos helped in identifying participants physical movements as well as their verbal conversations. SynergyView[4] video analysis tool was used to tag the video time-line with specific remarks, codes, and colours that is used later in consolidating the output into meaningful results that can be incorporated in the related aspect of the analysis.

All video recordings have been watched and analysed using the tool. Each group has three videos, one for both participants working together in co-located scenario, and two

[4] SynergyView is a video time-line analysis tool developed by TEL research group in Durham University [4].

separate videos for each one while they were working individually in distributed scenario. Appendix D presents a sample of the output of the SynergyView analysis tool.

3.3.3 Dealing with outliers

Outliers present a threat on data analysis because they might greatly alter the results of statistical tests as they bias the mean and inflate the standard deviation [41]. Outliers are defined as those readings in the collected data that are extremely off the mean of the whole data. Grubbs [48] defined it as:

> "An outlying observation, or outlier, is one that appears to deviate markedly from other members of the sample in which it occurs."

Outliers may appear in the data as a result of measurement errors or merely by a chance. There is a lot of debate on how to deal with these scores; the argument is about whether to completely eliminate the outliers by removing them from the data set, or by applying some statistical methods that are claimed to correct their effect on the data [41]. In this research, eliminating the outliers was the choice as it is a safer proven method; and the detection procedure revealed that only *one* group is to be eliminated, which should not greatly affect the sample size.

3.3.3.1 Outliers detection

The most frequently used method for detecting outliers is by plotting the data variables in concern using a box plot [41]. Figure 3.4 illustrates the box plot for the *effort* variable[5] in co-located condition. In this figure, it is noticed that there is an odd single point on top of the plot just above 300, that point is considered an outlier. Looking at the scores for the *effort* variable, this score belongs to group number 10.

The other method is by using some statistical tests[6] to detect outliers. One of the most common tests is the Grubbs test which gives the following results:

[5] *Effort* is part of efficiency analysis; explained in Subsection 5.2.1.

[6] These tests include: Grubbs test, Dixon's Q, Peirce's criterion, and Chauvenet's criterion.

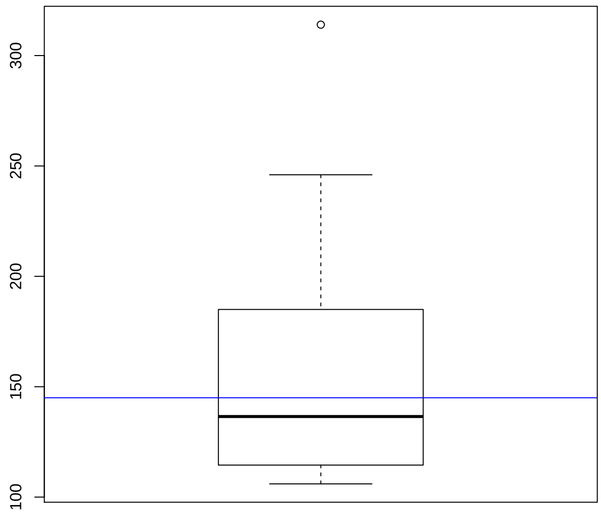


Figure 3.4 – Outlier detected in *effort* variable

> Using Grubbs test for the *effort* variable in co-located condition, the test reveals that score 314 which belongs to group 10 is an outlier, $p \leq 0.05$.

The formal method shows the same result as the visual box plot method; group 10 is an outlier in the score of *effort* variable. Actually, group 10 tends to be an outlier for many other variables in both scenarios. The reason for this is the way the two participants in that group were performing the task as observed by the researcher and was, also, obvious in the video records. Each one of them was quickly tapping the answer boxes with two finger without paying attention to the questions and answers. While this strategy made the group extremely fast, but the results was also extremely inaccurate and unsuitable for the purpose of the study.

3.3.3.2 Outcomes

Although the original number of participants was 32 who were grouped into 16 pairs, the outlier pair has been eliminated, and hence, the actual number of participants who is taken into consideration in this research is 30 grouped into 15 pairs; 8 groups started with co-located scenario then distributed, and 7 groups just did the opposite (see Table 3.1).

3.4 Answering Research Questions

To answer the research questions proposed in Subsection 1.4.1, a set of investigations are designed to analyse the cause and effect between the independent variable (*scenario*) and other dependent variables. Ideally, the following conditions should hold to infer *cause* and *effect* relationship (Field [42]):

1. Cause and effect must occur close together in time
2. The cause must occur before the effect does
3. The effect should never occur without the presence of the cause
4. All other explanations (*confounding variables*) of the cause-effect relationship are ruled out

In other words, an effect should be present when the cause is present, and when the cause is absent the effect should be absent too. This cause and effect relationship is the essential measure of validity as will be explained in Section 3.6. The only way to ensure that these conditions are there so we can infer a causality relationship is through the comparison of two controlled situations (or *experimental conditions*): one in which the cause is *present*, and one in which the cause is *absent*. In this research, the condition to be changed in the experiment is the location of tabletops; therefore, cause is present means users are distributed, while cause is absent means users are co-located. These conditions were illustrated previously in Figures 3.1 and 3.2.

All investigations include comparisons between the means of variables in the two conditions. It is important to know that this is not a simple arithmetic comparison, it is a statistical comparison based on the statistical methods described earlier in this chapter in Section 3.2. In addition to comparisons, correlation analysis among the variables in each condition is also carried out. These investigations are briefed in Table 3.3, and explained in detail in the next subsections. The statistical analysis and results of each investigation are presented in Chapter 5.

Investigation number	Investigation area name	Investigation outline
1	Performance analysis	• Compare the means of users performance variables between the two conditions • Compare the correlations strength among users performance variables between the two conditions
2	Collaboration analysis	• Compare the means of users collaboration variables between the two conditions
3	Usability analysis	• Compare the means of system usability variables between the two conditions • Compare the correlations strength among system usability variables between the two conditions
4	Correlation analysis	• Compare the correlations strength among variables in the three areas between the two conditions

Table 3.3 – Investigations to answer the research questions

3.4.1 Investigation 1: Users performance analysis

Users PERFORMANCE has two sub-areas to be investigated, *Efficiency* and *Accuracy*. Each area includes a set of variables as presented in Subsection 3.1.2. The investigation is done on these variables as follows:

- For *Efficiency*
  - Compare the means of *duration* in both scenarios
  - Compare the means of *effort* in both scenarios
  - Compare the means of *speed* in both scenarios

  - Compare the correlation strength among all *Efficiency* variables between both scenarios

- For *Accuracy*
  - Compare the means of *incorrectness ratio* in both scenarios
  - Compare the means of *added difficulty ratio* in both scenarios
  - Compare the means of *unnecessary work ratio* in both scenarios
  - Compare the correlation strength among all *Accuracy* variables between both scenarios

- Compare the correlation strength among all PERFORMANCE variables between both scenarios

3.4.2 Investigation 2: Users collaboration analysis

Users COLLABORATION has three sub-areas to be investigated, *Styles*, *Communication*, and *Balance*. Each area includes a set of variables as presented in Subsection 3.1.2. The investigation is done on these variables as follows:

- For *Styles*:
  - Compare the means of *CH style* in both scenarios
  - Compare the means of *VE style* in both scenarios
  - Compare the means of *SSP style* in both scenarios
  - Compare the means of *SGP style* in both scenarios

- For *Communication*:
  - Compare the means of *frequency* in both scenarios
  - Compare the means of *start time* in both scenarios
  - Compare the means of *interval* in both scenarios
  - Compare the means of *help initiation* in both scenarios
  - Compare the means of *help response* in both scenarios
  - Compare the means of *response time* in both scenarios

- For *Balance*:
  - Compare the means of Gini index of *work contribution* in both scenarios
  - Compare the means of Gini index of *communication contribution* in both scenarios

3.4.3 Investigation 3: System usability analysis

System USABILITY has three sub-areas to be investigated, *Satisfaction*, *Ease of learn and use*, and *Physical and cognitive demand*. These areas do not include sub-variables as in the previous two areas, so each area is considered as a variable to be investigated as follows:

- For *Satisfaction:*
  - Compare the means of *Satisfaction* in both scenarios
- For *Ease of learn and use:*
  - Compare the means of *Ease of learn and use* in both scenarios
- For *Physical and cognitive demand:*
  - Compare the means of *Physical and cognitive demand* in both scenarios
- Compare the correlation strength among all USABILITY variables between both scenarios

3.4.4 Investigation 4: Correlation analysis

A general correlation analysis among all the variables in all areas shall demonstrate the strength of effects between each two variables. This will be carried out as follows:

- Compare the correlation strength among all PERFORMANCE and COLLABORATION variables between both scenarios
- Compare the correlation strength among all PERFORMANCE and USABILITY variables between both scenarios
- Compare the correlation strength among all COLLABORATION and USABILITY variables between both scenarios

3.5 Analysis Framework

Each of the investigations introduced in Section 3.4 shall produce results that are presented in Chapter 5. These results are generated using a group of statistical methods, which have been described in Section 3.2.

The analysis procedure below has been developed to put all the investigations in a consistent framework that goes through the process of statistical analysis step by step. A series of tests are performed on the data for each of the investigations in Chapter 5. For each of these tests, a formal statistical result is produced along with its significance.

The general steps for investigating the research areas are:

1. For each study area (Performance, Collaboration, Usability)
   a) Investigate the significance of differences between all outcomes in the two conditions *(t-test for differences in means)*
   b) If applicable[7], investigate the correlation between all the variables in the two conditions *(Pearson's correlation test)*
   c) Compare the correlation coefficients resulted in step (1.b) in the two conditions *(Fisher's z-Transformation test)*
2. Investigate the correlation between all variables in the two conditions for
   a) Performance and Collaboration *(Pearson's correlation test)*
   b) Performance and Usability *(Pearson's correlation test)*
   c) Collaboration and Usability *(Pearson's correlation test)*
3. Compare the correlation coefficients resulted in step (2) in the two conditions *(Fisher's z-Transformation test)*

Each step's result is reported with an explanation of whether it validates the proposed hypothesis or not. The results are also supported with graphical charts representations to aid in understanding their interpretation.

[7] There is no correlation analysis carried out in the collaboration area.

3.6 Threats to Validity

In scientific experiments, the independent variable is often manipulated to see what effect it has on a second variable (the dependent variable). In this research, for example, the location of participant is changed to see its effects on some of HCI aspects, such as usability and performance. The purpose of this method is to make a causal inference, that is, that different physical locations of participants may be held responsible for observed differences in HCI aspects. When this causality relationship can be confidently attributed to the observed changes or differences in the dependent variables to the independent variable, and other explanations are ruled out, then this causal inference is said to be *internally valid* [79].

In most cases, however, the effects found in the dependent variable may not be just because of the variations in the independent variable. Rather, confounding uncontrollable variables may lead to additional or alternative explanations for the effects found and/or for the magnitude of the effects found. Therefore, internal validity is considered as more of a matter of *degree* rather than a valid or invalid case. That is why experimental research designs should target results with a high *degree* of internal validity.

In order to obtain results with a high degree of internal validity, experimental work must be designed carefully with the objective to minimise confounding and uncontrolled circumstances to increase the sensitivity of the measured dependent variables to variations in the independent variable [35]. Generally, conclusions drawn on the basis of direct manipulation of the independent variable are considered valid in controlled experiments with random selection, random assignment to conditions, and reliable instruments [79].

The following are the most well known threats to internal validity in scientific research as described by Wortman [154], and how they can be eliminated or minimised during the experimental work of this research:

Testing effects: Repeatedly engaging the participants in experiment conditions may lead to bias. Participants may remember the correct answers or may be conditioned to know that they are being tested. This threat to validity is hard to eliminate in within-subjects designs, but can be reduced to a minimum level by counterbalancing the conditions order, which has been taken into consideration in this study as shown in Subsection 3.1.1.2.

History: This means history large scale events (e.g. natural disaster, political change, etc.) outside of the experiment that may affect participants attitudes and behaviours during the experimental procedures. This threat was not applicable during this research.

Instrument: Devices used during experiments may have great effects on the outcomes. This could happen as a result of the devices calibration or external factors that alter the devices expected performance. In this research, two multi-touch tabletops were used for the experiment. These tables use infrared sensors in order to capture users touches. The experiment was conducted during summer months and the room was very warm and humid in some sessions. That negatively affected the performance of some participants who found the tables unresponsive and inaccurate. This threat can be eliminated if the experiment is held in a more suitable temperature environment, e.g. by using air conditioning; however, such solutions were not feasible during this research.

Statistical regression: This happens when some of the outcome readings tend to be extremely far form the mean. The most known source of this threat is the presence of outliers in the data set. In the results of this experiment, the results of a group of two participants have been totally removed form the data set as they were considered outliers because the participants were using a wrong "thoughtless" way to solve the given problem. The problem of outliers has been dealt with in Subsection 3.3.3.

Maturation: This happens when subject change during the experiment sessions. For example, participants may perceive the second part of the experiment easier because they already have passed through a similar experience in the first part. They might also be more bored and fatigued in the second part. These changes may affect the way a subject would react to the changes in the experiment condition. Counterbalancing and shortening the time of the session have great effect in reducing this threat [78]. That have been considered when designing the experiment (Section 3.1) and conducting a pilot study (Subsection 3.7.1).

Experimental mortality: This threat occurs when the results are based on the completion of the experiment by all participants, who were enrolled in it at the first place, but some of them have not actually finished the experiment. In the case of this study, none of the enrolled participants has withdrawn before the end of the session, therefore, this threat is not applicable.

3.7 Experiment Sessions

To put the used method in context, a full experiment session is shortly described in this section. This will aid in understanding the nature of the experiment and how the outcomes are captured and measured. A description of the room layout is also presented. This will put the used application into perspective when it is explained in Chapter 4.

3.7.1 Pilot experiment

A group of volunteers have been used before the official experiment in order to fine tune the application, environment, cameras, and session length. The objectives of this pilot study are:

- Capture any serious bugs in the software in order to fix them before the actual experiment
- Make sure that the cameras and microphones are well configured and in the right positions
- Test the automatic system logging service
- Test the questionnaires to find out how much time do participants need to complete them and whether any question have ambiguity
- Find out how long do other aspects of the experiment take, such as filling consent forms, welcoming and introduction, run a demo, etc.

As time is a major factor for participants, the study aimed at making the sessions as short as possible. By testing the scenarios for several times, it was possible to fine tune the graph and questions used in the game to make the whole session last for a maximum of 45 minutes, including filling the questionnaires and other introductory aspects.

3.7.2 Experiment theatre layout

Figure 3.5 illustrates the abstract layout of the space where the experiment is commenced. Figure 3.2 shows a real picture of the experiment room. Note that for the co-located scenario, the participants use only one of the tables.

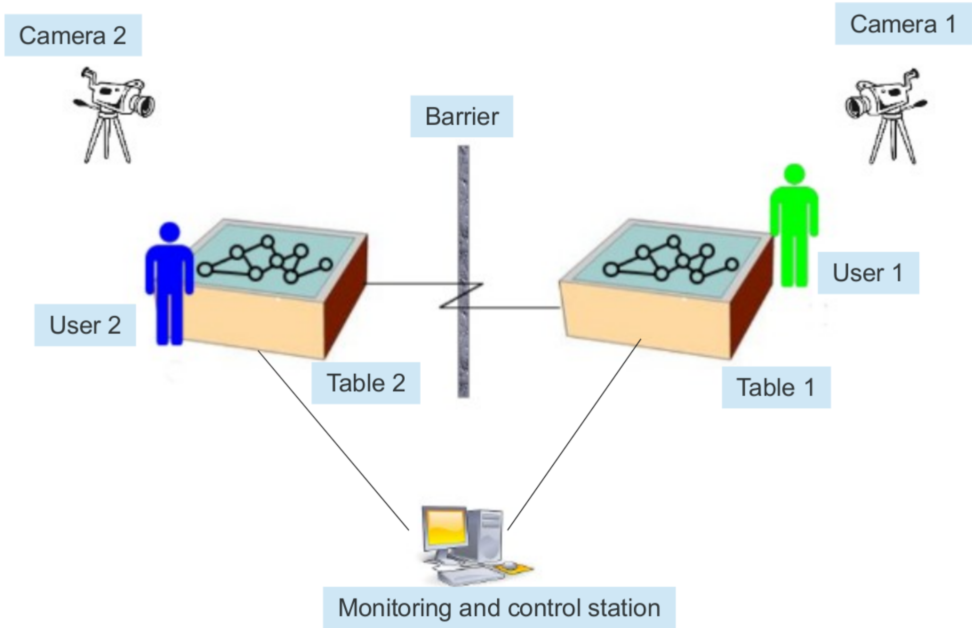


Figure 3.5 – Abstract layout of the experiment space

Tables are connected to display exactly the same content to each participant in the distributed scenario as described later in Chapter 4. A special separate computer is used to control and monitor both tables, then to copy the logs generated during the experiment from each table. Cameras are configured and positioned in fixed places in the room for the whole period of experimentation (about two weeks).

An important point to mention is that, ideally, each table should be in a totally separate room in the distributed scenario. But, it is very impractical to move these tables because they are large, heavy, and very sensitive. In addition to that, they are configured and calibrated for other experiments in that room as well. A large temporary barrier is used to separate the two tables in a way that both participants cannot see each other nor the other table (Figure 3.2), and they are requested not to talk to each other.

3.7.3 Experiment session procedure

After contacting the interested participants, the schedule is coordinated to suite both of them as well as the availability of the experiment room; then a time slot is booked for their session. Below, is the whole procedure of an experiment session that starts with the co-located scenario:

1. Prepare the room
    a) Start up the tables
    b) Start up the monitor and control server
    c) Test run the application
    d) Video cameras stand-by
    e) Still shots camera ready
    f) Edit the configuration file
        i. Scenario (co-located)
        ii. Participants names
    g) Get forms ready to be filled
        i. Consent forms
        ii. Questionnaires
2. Participants welcoming
3. Briefing of the research and its purpose
4. Participants fill the consent forms
5. Participants sit together to the same table
6. Run a short demo for the co-located scenario
    a) Participants practice some required skills to interact with the application
    b) Answer any questions that participants may have
7. Start the first part of the experiment (co-located)
    a) Start the application in co-located condition
    b) Start video recording
    c) Monitor the application for any technical troubles
    d) Take still pictures for the participants in action
8. First part finishes
    a) Stop video recording
    b) Stop the application
9. Participants fill the questionnaires for the co-located scenario
10. Configure the application for the distributed scenario

11. Run a short demo for the distributed scenario
    a) Participants practice some required skills to interact with the application
    b) Answer any questions that participants may have
12. Participants separate to use two different tables
13. Start the second part of the experiment (distributed)
    a) Start the application in distributed condition
    b) Start video recording
    c) Monitor the application for any technical troubles
    d) Take still pictures for the participants in action
14. Second part finishes
    a) Stop video recording
    b) Stop the application
15. Participants fill the questionnaires for the distributed scenario
16. Answer any questions they may have and take notes and comments from them
17. Thank participants before they leave
18. Copy the system logs to be analysed
19. Shut down the tables
20. Shut down the control and monitor server
21. Copy the video recordings and still pictures to be analysed
22. Write down notes about the session

The experiment procedure that starts with the distributed scenario follow the same steps but with distributed scenario as the first part of the experiment then the co-located scenario as the second part.

3.8 Chapter Summary

In this chapter, the method used in this research has been introduced. An overview of the experiment design techniques and data analysis approaches have been presented with justification of why specific tests were chosen for this study. Variables were also defined with their roles in the data analysis. The data sources that are used in this research are presented along with how they get prepared and cleaned for analysis. A framework for procedural statistical analysis is proposed to aid in answering the research questions. Threats to validity were discussed as well as the ways to avoid or minimise them. And finally, a briefing of the experiment session procedure is illustrated to put the used methodology in the context of this research.

In the next chapter (System Design), the system that is designed and built for the purpose of this study is presented. The architecture, user interface, interactions, and game logic are demonstrated to show how this system shall assist in collecting the required information to test the research hypothesis using the methods described in this chapter.

4 System Design

In this chapter, the design of the software used in this research is described. First, the game scenario is explained to set the objectives of the application. A high level architecture of the application is presented to show how the major components are put together. The user interface is discussed and the interactions needed with the application are also explained with a briefing of the services implemented to support that.

4.1 The Game

In order to implement the methodology described in the previous chapter, an application is designed and built in a way that will help to test the effects of distribution on the considered HCI aspects. The designed system should:

1. Support synchronous interactions of two participants
2. Have the ability to run in co-located and distributed conditions
3. Not be very complicated or very trivial to work with
4. Help in conducting experimental sessions in optimum time and effort

As Manninen [81] stated, "games and game-like activities offer enormous potential for practitioners and researchers. While the game setting itself can be of great value, there is also the additional benefit of acquiring research material from these playing sessions. Because the game system has been designed with the research task in mind, it adequately supports various forms of data collecting (e.g., video capture, observer views, control mechanisms and log files)." Distributed multi-player games are well known applications that support synchronous interactions. Optimising experimental sessions time and complexity of the scenario are achieved by the pilot study as explained in Chapter 3.

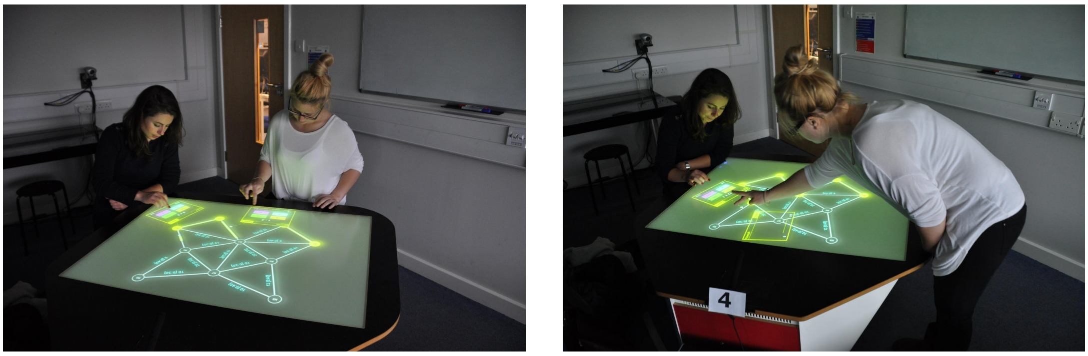
4.1.1 Supporting the aspects of the research

The game is based on achieving a goal within a time limit; that will enable measuring the first aspect of the research which is the players performance. The goal of the game cannot be achieved without the two participants being working together; therefore, the collaboration work can be analysed to fulfil that aspect of the research as well. And finally, participants are requested to fill in some questionnaires that will support the analysis of the usability of the system in both scenarios, which is the third aspect of this study.

4.1.2 Application specifications

The game resembles a sort of a racing against time to achieve a common goal for both participants who work together as a team. The goal of the game is to visit all the nodes in a connected indirect graph in the most efficient way (time and effort) before time is up and game is over. Players start from pre-defined nodes on the graph and have to move to the next possible nodes using the links of the graph. To use a link, the players have to select the link and solve a certain number of questions assigned to that link in a pre-determined time. These questions are generated randomly and they consist of basic arithmetic operations. The reason of choosing basic arithmetic operations to form the questions is because arithmetic signs and numbers are universal and can be understood by any one, which will simplify the process of finding participants for the study. If they could solve all the questions of the link, then the node connected to the link is said to be visited, and the players can move on to the next link(s) and node(s). If they fail to solve all the link's assigned questions before the link's time is up, the link is reset and they have to restart working on it again. Links vary in their difficulty; the shorter the time and greater the number of questions, the harder the link is to be finished. Some links are very easy to solve by one player, and some others are impossible to finish without the cooperation between both players; this feature can greatly help in studying the cooperation level between both participants to see when they work individually in parallel (to maximise their performance) and together (to overcome a difficult obstacle). Player should be able to contact each other in both scenarios to ask for help in difficult situations. Visual clues of progress, time, and contact are provided to the players to help them during the game session. Once all the nodes are marked visited, the game ends and the players can no longer interact with the system.

The application should also support some of the basic features of the multi-touch surfaces, such as rotating and translating some of the interface objects to suit the player's physical position around the table which may change according to the area of the active part of the graph and to the player's preference. An example of this feature is illustrated in Figure 4.1.



(a) (b)

Figure 4.1 – Players can change their physical position around the table

4.1.2.1 Game start

The game starts with a graph that have unvisited nodes connected with links, and two unattached empty panels tagged with the players names. Two of the nodes are marked visited by default, those are the starting nodes. This is illustrated in Figure 4.2.

4.1.2.2 Selecting a link

To select a link to work on, a player should touch that link and drag a connector line to his/her panel. This process is called attaching a link to a panel (Figure 4.3). Each panel can be attached to only one link at any given time (Figure 4.4). However, a link can be attached to both panels if the two players decide to work on it together (Figure 4.5). The progress over a link can be visually tracked by displaying a coloured progress bar with each link as shown in Figure 4.4 for example.

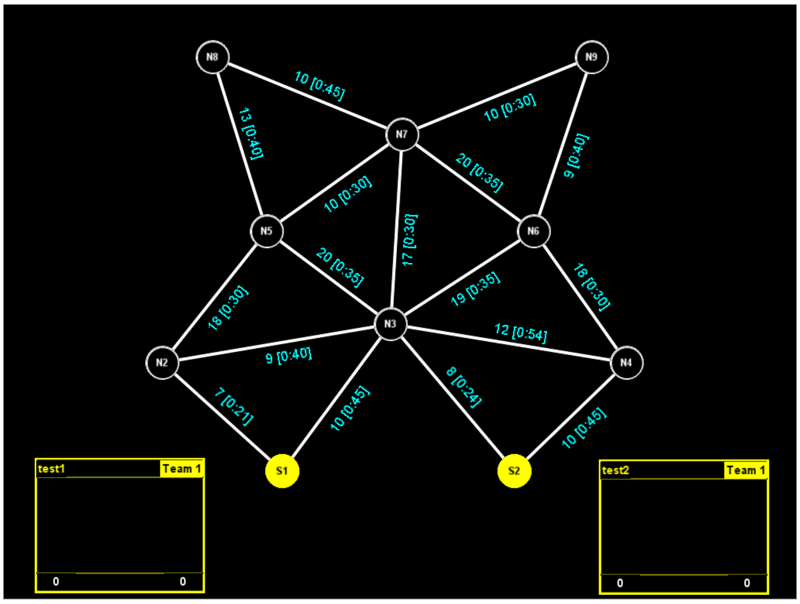


Figure 4.2 – Game start

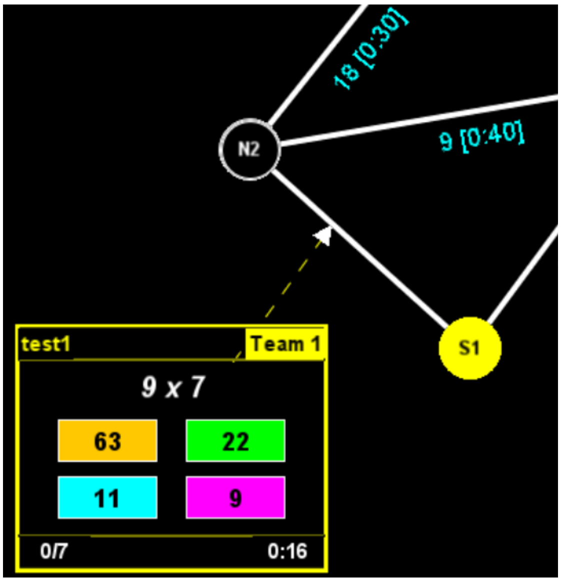


Figure 4.3 – A link attached to one panel

4.1.2.3 Panels

Panels are the areas of the workspace where players solve the link's questions, monitor their progress over a link, and communicating with each other in the distributed scenario. Link's questions are displayed sequentially in a random order with four possible answers.

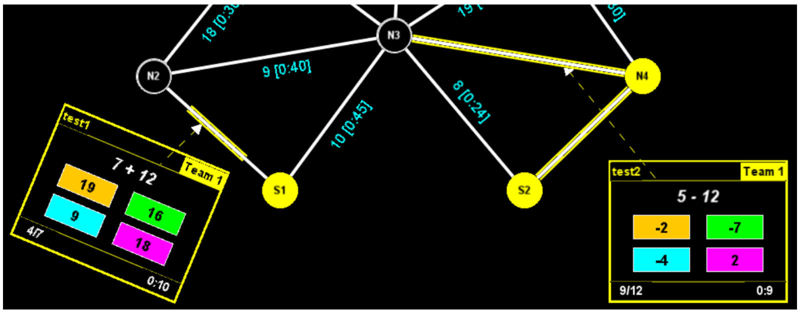


Figure 4.4 – Two links attached

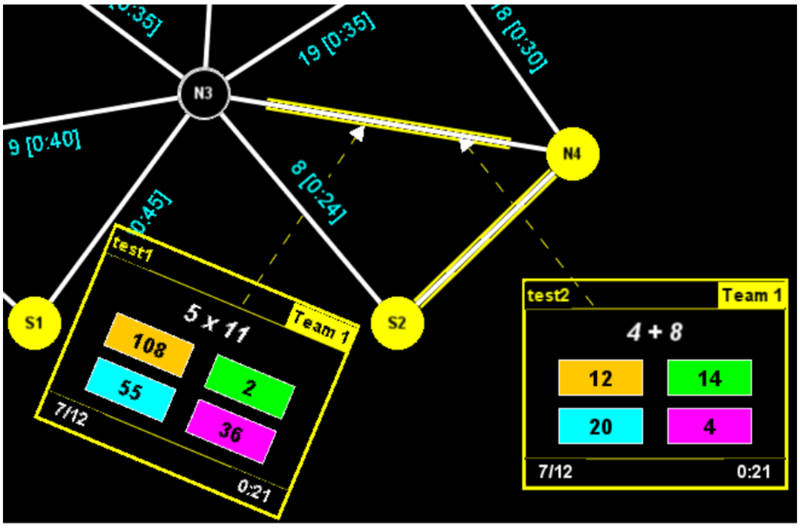


Figure 4.5 – A link attached to both panels

One of the answers is the correct one, the other three are wrong. A player can select an answer by simply touching it. Once an answer is selected, the player is immediately provided with the next question until the link's assigned time is over, or the link's assigned questions are all solved. Selecting the correct answer will cause a progress on the link, while selecting a wrong answer will have no impact but it will slow down the progress. A panel is illustrated in Figure 4.9.

4.1.2.4 Distributed assistance

In the distributed scenario, players are provided with a simple messaging system to ask for help or to offer help. Players can use this system from their panels. When a player asks for or offers help, the other player gets notified by a short message displayed on top of his/her panel, along with two answering buttons to reply with “YES” or “NO”. Once a reply is sent by the second player, the first player gets notified as well. If the answer was “YES”, the other player’s panel is automatically attached to the first one’s link, and they immediately can continue together without losing the progress made on that link. This feature is not found on the co-located scenario where players have to manually attach their panels when they want to work together on the same link.

4.2 High Level Architecture

This section describes the high level architecture of the application framework used to build the software. It also describes in more details the application’s internal structure and data flow among different components.

4.2.1 SynergyNet framework

SynergyNet is a framework developed by Technology Enhanced Learning research group at Durham University [3, 57] to operate multi-touch tables and provide the basic user interface components and interactions to build multi-touch applications. The objective of building such a framework is to give the researchers the maximum flexibility and power of open source software, and to be able to customise the applications they want to use in their experiments. It has been developed using java language, and been thoroughly tested and enhanced over several other studies and experimentation works.

Figure 4.6 illustrates the main layers that make the SynergyNet framework [82, 110]. A short description of each layer is following.

Application: This is where the actual application is built. It should use the libraries provided by the lower layers in order to work within the SynergyNet environment. More on the application in Subsection 4.2.2.

AppSystem: This is an organising layer that control all the applications within the SynergyNet workspace, and provides the means of starting and closing the applications, as well as switching between them.

Content System: The essential user interface components are built in this layer. Those include components such as buttons, frames, text labels, colours, etc. Any

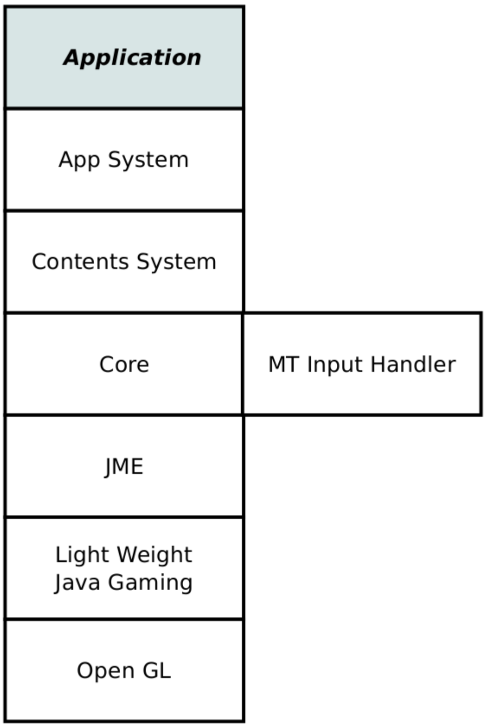


Figure 4.6 – SynergyNet framework architecture

SynergyNet application should either directly use these components or extend them to add more features.

Core: This is where the actual multi-touch work is done. This layer has two sub-components:

- **Multi-touch Input Handling:** Where the user's touch points (called blobs) are captured and encapsulated in manageable objects.
- **JME:** jMonkey Engine, is a collection of graphical libraries and tools used to develop graphical applications such as 3D games and sophisticated user interfaces.

Lightweight Java Game Library: This is a java library used in complex graphics applications to interact with the next lower layer which is OpenGL.

OpenGL: This layer is the lowest one and consists of a set of libraries that interact directly with the graphics hardware. It is used to efficiently render graphical components in graphics intensive applications.

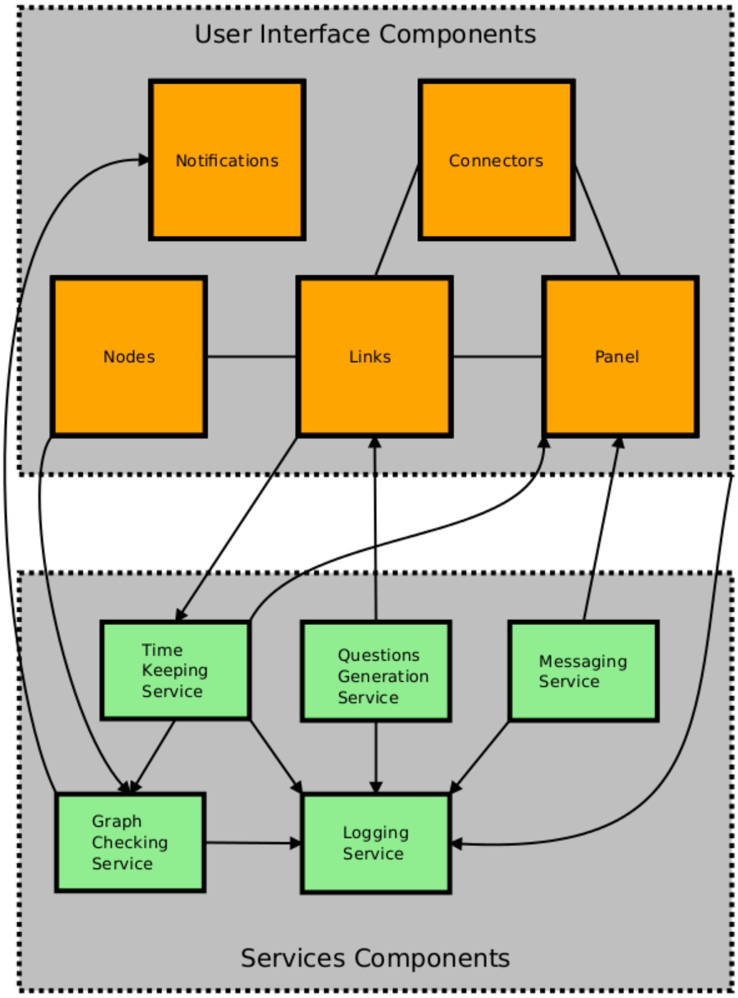


Figure 4.7 – Application structure

4.2.2 The application

As mentioned in Section 4.1, the game is about traversing a graph to cover all of its nodes in the shortest time. The application should take the mentioned specifications into consideration. The application structure can be split into two major layers with sub-components in each one. The first layer is the user interface layer which is responsible for displaying the different components on the multi-touch tabletop, and the second one is the services layer which is responsible for the logic of the application and exchanging data with the first layer. This is illustrated in Figure 4.7, with data flow interactions among the different components as well.

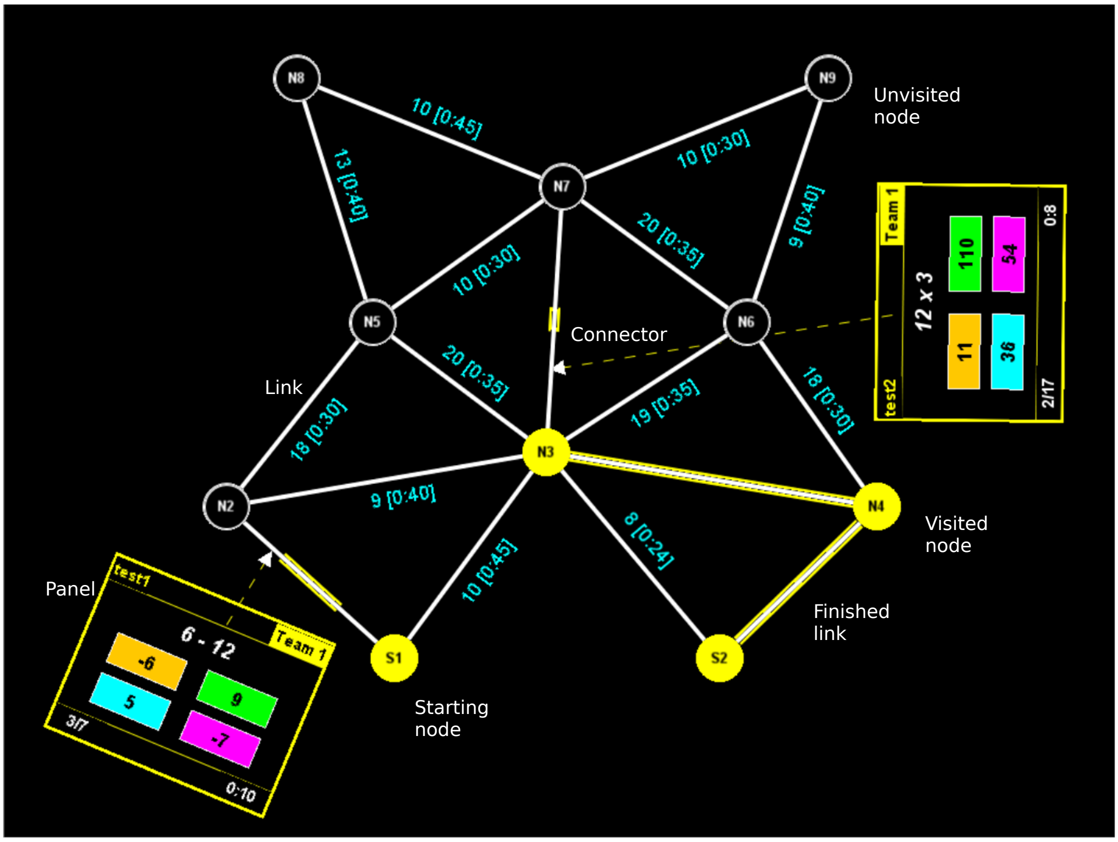


Figure 4.8 – Visual components

4.2.2.1 User interface components

Figure 4.8 shows a screen shot of the user interface that illustrates the visual components described in this subsection.

Panels: Are where the participants work most of the time in this game. Each participant has his/her own panel where they can:

- Select the questions answers
- Contact the other participant (in distributed scenario)
- Get notified of messages from the other participant
- Track the remaining time of the connected link
- Track the progress of the connected link

Panels receive their input from the connected link (via the connector component), messaging service, and time keeping service. A panel has the participant's name displayed on it, and can be rotated and moved around the surface of the table to suit the participant's position. This component is illustrated in Figure 4.9.

Links: Are the core of the game logic. The actual progress in the game depends on how the participants progress over the links. The initial state of a link is a white line connecting two nodes in the graph, with the number of questions associated with this link and the time allowed to solve the questions. Once participants start to solve the questions associated with a link, another line in a different colour starts to cover the initial link to indicate progress. A link's questions can be solved in a connected panel(s). Each link can connect to two panels at the same time, so both participants can work on it to increase the speed of their progress. Links receive their data input from the question generation service, and send their specific time allowance to the time keeping service.

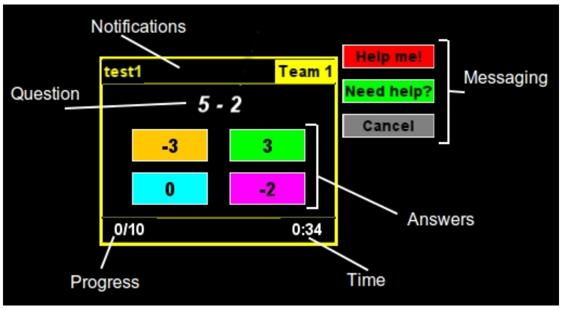


Figure 4.9 – The panel component

Nodes: Nodes are the targets of the game as described earlier. They are initiated as empty circles with *unvisited* state, then filled when participants reach them via links and their states changed to *visited*. Two special nodes are the starting ones, which they mark the starting points for both participants, and they are filled from the beginning. Nodes are associated with links, and send their states to the graph checking service, which checks whether all the nodes are visited or not.

Connectors: These are visual elements that are not part of the game logic itself, but they are the mechanism in which users can choose a certain link and work on in in their panels. This is done by touching the link, dragging a connector line, then connect it it to the panel. Each link can have a maximum of two connectors (one for each participant). Connectors are very dynamic elements, they can be extended and moved according to the position of the panel. They also help to give the players a quick visual clue of which link are they connected to.

Notifications: Notification component is used to display messages to the participants on top of all other visual components. Two types of notifications are implemented in this application:

1. Start notification: a message displayed at the beginning of the game to inform the participants of the objective of the game and the time they have to reach that objective. It is accompanied by a large button marked with "START" that player should press once they are ready to start the game.
2. Finish notification: a message displayed at the end of the game. It should have one of two states:
   a) Objective achieved, with the time spent in the game
   b) Game over, which means the participants have failed to achieve the goal within the allowed time

4.2.2.2 Services components

These are the main components of the application that are responsible for the underlying logic of the game and for providing the necessary data to other components. As shown in Figure 4.7, the services components interact with all other components in the system.

Questions generation: When the application is first started, a pool of questions is generated for the game using a randomisation algorithm written in Python. This algorithm generates unique questions and attach four answers with each one. One of the answers is correct, and the other three are wrong. All the questions and their answers are then stored in a data source to be used by other components in the application.
Once a link is created, a sub-pool of questions is constructed from the main pool and assigned to that link. Questions are randomly picked, and the answers order is also shuffled to minimise the repetition patterns. All actions of generation, assignment, and answering of questions are logged by the logging service.

Messaging: Messaging service is a crucial part in the distributed scenario as it is the only means of communication between the participants. Players can ask for help and offer help to each other using this simplified messaging mechanism. This service is activated and used through the user panel. When a user activates this service, he/she is provided with a set of buttons that suits the player's situation. Any action that the player takes with these messaging buttons is directly reflected to the other player's panel in the form of a message displayed in the notification area. A cancel button is also provided in case the player wants to deactivate the messaging service. All messages exchanged between players are logged by the logging service.

Logging: One of the major sources of data to be analysed is the system logs. These are automatically generated by the system and capture all the actions happened during the experiment run. Every entry in the log is time stamped along with user name and action done. In case it is not a user action, the component that initiated that action is logged instead of the user name. As shown in Figure 4.7, all components are connected to the logging service, including the whole user interface layer. A set of programs are written specially to extract the data from these logs as explained in Subsection 3.3.2.2.

Time keeping: This service is responsible for tracking the total time spent in the game as well as the time limit for each link. When the time is up for a certain link before the player finish it, this service causes the link to reset and return to its initial state, and it restart the timer again. If the time allowed for the whole game is up, it causes the game to end by informing the game checking service of that and to display a notification message that the game is over. As each participant needs a separate time keeping for his/her own progress, this service is implemented as a multi-threaded service. All timing actions logged in the system logs use this service to time stamp the entries.

Graph checking: This is a small service that keeps checking the state of all nodes as well as the time allowed for the game. It displays the notifications as mentioned in the notifications visual component. It takes its input from the nodes component and the time keeping service.

4.2.2.3 Connecting two tables

In the distributed scenario, both tables must display exactly the same objects for each user, and they must, also, capture both users touch input at the same time. The multi-touch tables used in this research use the TUI (Tangible User Interface) protocol to capture user's input and display output objects [5]. It takes its input from a visual system that in turn takes its input from the infrared sensors which are responsible for capturing the user's blobs. In the output stage, TUI updates the objects on the multi-touch surface

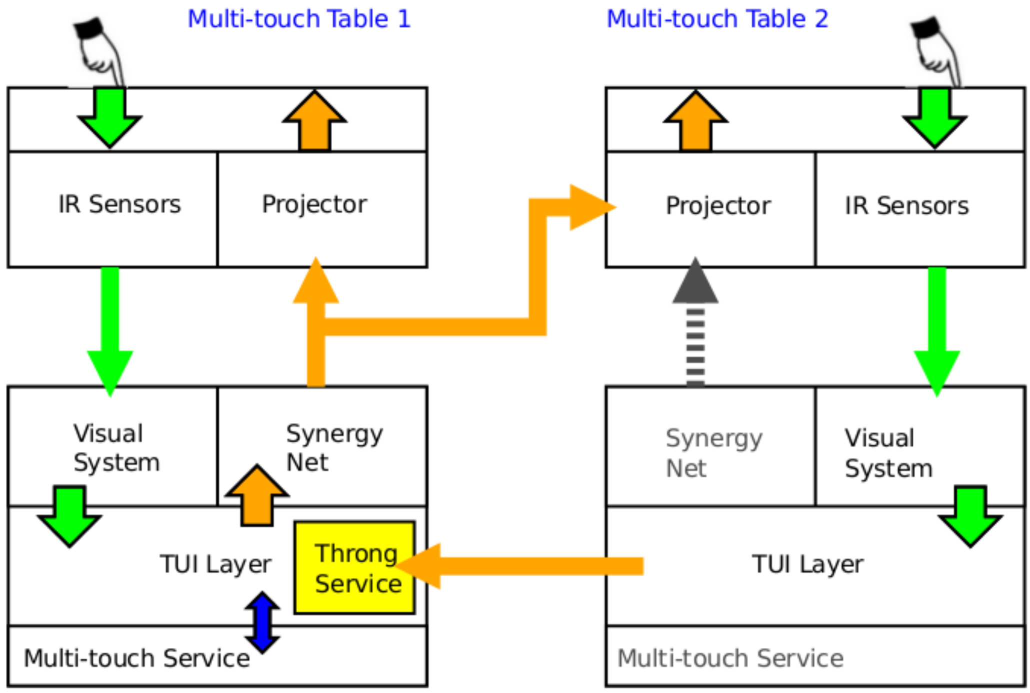


Figure 4.10 – Connecting two tables protocol

via the SynergyNet layer (described previously), which is responsible for sending the output signal to a projector. In both stages, input and output, TUI interacts with the underlying multi-touch service that is built in the operating system.

TUI is designed to work locally with one table, so a modification is needed in order to enable it to work with two tables. A service component is used for this functionality called Throng multiplexer [80]. Throng is a service designed to work with TUI protocol to provide several functionality extensions, such as being able to connect two multi-touch tabletops. It takes the output from the other table and multiplex it with the output of the first table, then sends all that to the TUI layer as a ready to display output. The second table's projector is physically connected to the output port of the first table, and that makes both tables display exactly the same objects for both users. Figure 4.10 illustrates how this technique is implemented to support the distributed scenario.

Notice that in the co-located scenario, only table 1 is used, and the Throng service is inactive. Once the experiment switches to the distributed scenario, the Throng service is activated, and SynergyNet and Multi-Touch services are disengaged in the second table; that will make TUI sends its output to the other table via the Throng service.

4.3 Chapter Summary

In this chapter, the system that is used for this research has been presented. An explanation of the game application is introduced to show how it will fulfil the requirements of the method to test the hypothesis of the research. The different aspects of the game and how it is played has been illustrated. A high level architecture is also presented with a briefing of the different visual and logical components used in the system and their interactions with each other.

5 Data, Analysis, and Results

This chapter presents the results produced by analysing the data that has been collected during the experimental work sessions. Results depend heavily on statistical analysis as the main source of supporting evidence of the research hypotheses. Three major areas of study were taken into consideration in this research: PERFORMANCE (in Section 5.2), COLLABORATION (in Section 5.3), and USABILITY (in Section 5.4). For each one of these areas, a briefing of the findings is presented in the form of descriptive statistics, then the hypotheses related to the area are tested by comparing the relevant data in both scenarios (co-located and distributed). A correlation analysis is also carried out to find out the effect of the experimental condition on the internal relationships among the sub-factors of the research's three areas.

All results are supported by statistical tables and graphs to make the interpretation easier. The **R** programming language was used as the statistical tool for this work[2]. **R** is an open source software environment for statistical computing and graphics with exceptional power and flexibility that helped a lot during the course of this research.

5.1 Results Interpretation

A brief description of the used statistical measures and charts is presented in this sub-section to aid in understanding the meaning of the statistical tests that have been carried out on the data resulted from the experiment.

5.1.1 Basic descriptive statistics

Mean: The average score of all the scores of a given variable.

Median: The middle score when scores are ranked in order of magnitude.

Mode: The score that occur most frequently in the given variable.

Standard Deviation (sd): The measure of the average spread of a variable scores about the mean value.

Interquartile Range (IQR): The limits within which the middle 50% of an ordered set of observations falls.

5.1.2 Graphs

Bar plots are used in this research to illustrate the differences between group scores for most of the variables in both scenarios. Blue and red horizontal lines are drawn along with plots to illustrate the mean value for co-located and distributed scores respectively. Matrix plots are used to depict the correlation r-coefficients and relationship tendencies when studying the correlation between the different variables. Also, to visually aid interpretation of these plots, the font shape and size of correlation coefficients is printed in proportion with the strength of the relationship, that is, the stronger the correlation the bolder and larger the font. When studying contribution balance, stacked bar charts are used to show the percentage of contribution for each participant.

5.2 Group Performance

Group PERFORMANCE during their work on the given task has been measured and analysed. Performance is an important feature to consider in human-computer interaction studies [78]; it mainly focuses on how efficiently and accurately a task has been done by the subjects who used the software application. In this section, PERFORMANCE related aspects are investigated and analysed in both conditions, co-located and distributed, the underlying factors are presented in the following subsections with the results discussed at the end of each subsection.

In this research, PERFORMANCE is measured by studying the data collected from groups in two major areas:

1. *Efficiency*
2. *Accuracy*

Efficiency measures time and effort related factors, while *Accuracy* measures quality of results related factors [50, 78]. For each one of these areas, a subsection will explain what it measures, what are the underlying sub-factors, and whether there is a significant difference in the scores between the two conditions of the experiment (co-located and distributed). After that, a correlation analysis is carried out among the sub-factors to see if there is a relationship that the underlying variables may suggest. Finally, a similar correlation analysis is also used to test the relationships between all sub-factors of PERFORMANCE, then a summary of all findings in this section is presented.

System logs and video recordings are used as the data source for this part of the analysis. Differences between the two experimental conditions, the co-located and the distributed, are investigated using the *paired-samples t-test* statistical method (see Subsection 3.2.3) to calculate the significance of the difference in means. Pearson's correlation test is used to measure the relationship strength among sub-factors (see Subsection 3.2.4). The reliability of the results is considered in a 95% confidence interval. Paired-samples t-test is used when the same group of subjects is used in all of the experiment conditions, which is the case of this experimental study.

5.2.1 Efficiency

Efficiency is a measurement of how fast a task can be completed; or, in other words, how long did it take a participant or a group to accomplish a given task using the application in concern, and in what speed of successful progress through the task [78]. Another factor of *Efficiency* is the effort needed by the user in order to finish a given task [107]. In the formal ISO standard 9241 for HCI[1], *Efficiency* is measured as the resources expended by the user(s) in relation to the *Accuracy*[2] and completeness of goals achieved[1]. High *Efficiency* is achieved when the user reaches his/her goals while expending as few resources as possible according to the mentioned ISO standard. Generally speaking, the less the time and effort put into the task, the higher the *Efficiency*. In this study, the task is to visit all the nodes in a given graph by traversing its links manually by solving

[1] "ISO 9241 provides requirements and recommendations for human-centred design principles and activities throughout the life cycle of computer-based interactive systems. It is intended to be used by those managing design processes, and is concerned with ways in which both hardware and software components of interactive systems can enhance human–system interaction." [1]

[2] Presented in Subsection 5.2.2

Sub-factor	Scenario	Mean	Median	SD	Min	Max
Duration (m:s)	**Co-located**	5:17	4:30	2:12	3:05	10:00
	Distributed	6:21	6:08	2:33	2:49	10:00
Effort (questions)	**Co-located**	145	131	40.7	106	246
	Distributed	212	189	71.8	114	364
Speed (Q/min)	**Co-located**	26.9	26.2	6.3	14.6	38.6
	Distributed	30.4	28.5	6.7	20.5	44.2

Table 5.1 – Basic descriptive results for *Efficiency* sub-factors

a certain set of questions (refer to Chapter 4 for details of the task). Three sub-factors are taken into consideration under *Efficiency* in this research:

Duration: Total time that a group spent on the task (from start to finish/game over).

Effort: Total number of questions a group has solved during the game (including correct and wrong answers).

Speed: Number of correctly answered questions *per minute* (the answers that cause progress).

To calculate the *Efficiency* sub-factors for each group, this research used the data extracted from system logs and video recordings of experiment sessions as explained previously in Chapter 3. First, it is necessary to find out whether there is a significant difference for each of these sub-factors in both scenarios, then the relationship among them is studied.

5.2.1.1 Basic descriptive findings

In this subsection, the basic descriptive statistical findings are presented in Table 5.1 for the three aforementioned sub-factors of *Efficiency*: *duration*, *effort*, and *speed* in the two conditions.

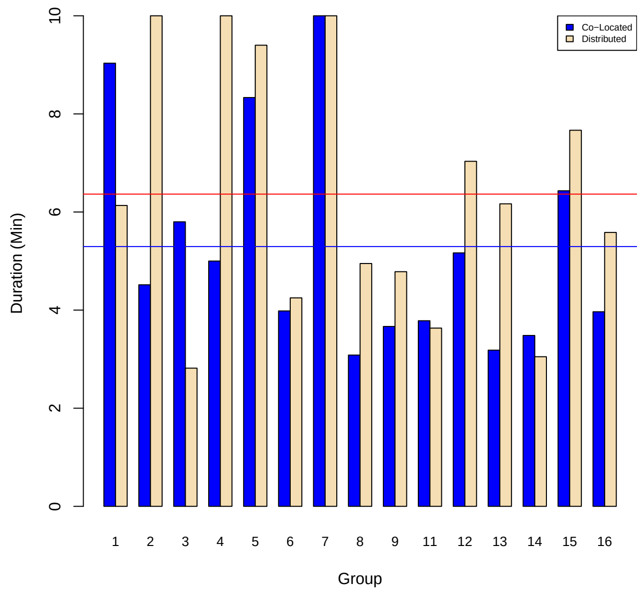


Figure 5.1 – *Duration* differences between the two conditions

5.2.1.2 Investigating differences

Duration

***Hypothesis P.1**: There is no difference between the means of duration in the two conditions.*

A paired-samples t-test was conducted to compare the *duration* in the co-located and distributed conditions. There was no significant difference in the scores of *duration* for the co-located and distributed conditions; $t(14) = -1.75$, $p > 0.05$, (95% confidence interval: -2.38, 0.24). Figure 5.1 illustrates the *duration* differences between the two conditions for all the groups.

Hypothesis **P.1** test: **Fail to Reject**.

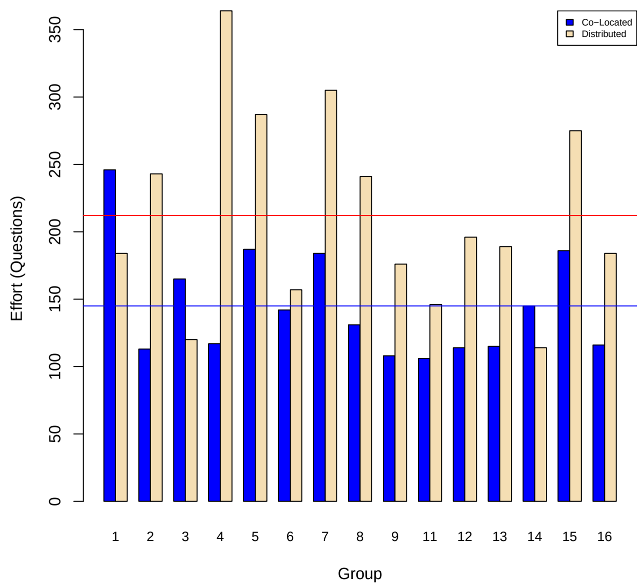


Figure 5.2 – *Effort* differences between the two conditions

Effort

Hypothesis P.2: *There is no difference between the means of effort in the two conditions.*

A paired-samples t-test was conducted to compare the *effort* in co-located and distributed conditions. There was a **significant** difference in the scores of *effort* for the co-located and distributed conditions; $t(14) = -3.33$, $p \leq 0.05$, (95% confidence interval: -110.27, -23.86). Figure 5.2 illustrates the *effort* differences between the two conditions for all the groups.

Hypothesis **P.2** test: **Reject**.

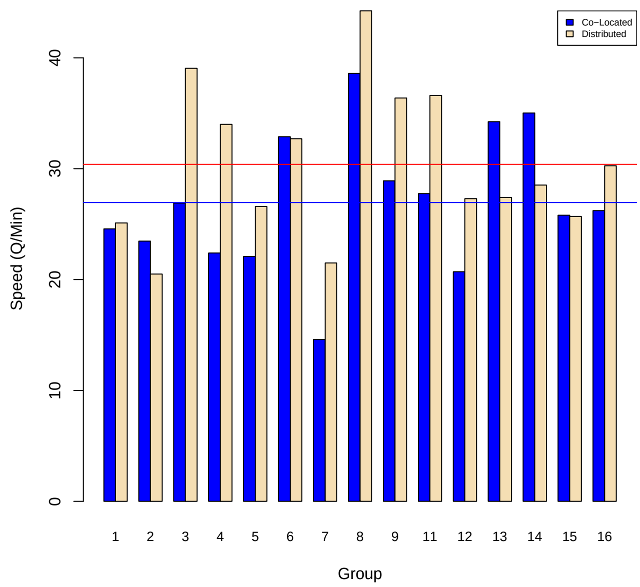


Figure 5.3 – *Speed* differences between the two conditions

Speed

Hypothesis P.3: *There is no difference between the means of speed in the two conditions.*

A paired-samples t-test was conducted to compare the *speed* in co-located and distributed conditions. There was a **significant** difference in the scores of *speed* for the co-located and distributed conditions; $t(14) = -2.24$, $p \leq 0.05$, (95% confidence interval: -6.74, -0.15). Figure 5.3 illustrates the *speed* differences between the two conditions for all the groups.

Hypothesis **P.3** test: **Reject**.

5.2.1.3 Sub-factors correlation

To get a deeper understanding of the *Efficiency* sub-factors and their interrelationships, a correlation test between them is conducted to see how they interact and affect each other.

	Co-Located			Distributed		
Group ID	***Duration*** (m:s)	***Effort*** (Q)	***Speed*** (Q/Min)	***Duration*** (m:s)	***Effort*** (Q)	***Speed*** (Q/Min)
1	9:02	246	24.6	6:08	184	25.1
2	4:31	113	23.5	10:00	243	20.5
3	5:48	165	26.9	2:49	120	39.1
4	5:00	117	22.4	10:00	364	34.0
5	8:20	187	22.1	9:24	287	26.6
6	3:59	142	32.9	4:15	157	32.7
7	10:00	184	14.6	10:00	305	21.5
8	3:05	131	38.6	4:57	241	44.2
9	3:40	108	28.9	4:47	176	36.4
11	3:47	106	27.8	3:38	146	36.6
12	5:10	114	20.7	7:02	196	27.3
13	3:11	115	34.2	6:10	189	27.4
14	3:29	145	35.0	3:03	114	28.5
15	6:26	186	25.8	7:40	275	25.7
16	3:58	116	26.2	5:35	184	30.3
mean	*5:17*	*145.0*	*26.9*	*6:22*	*212.1*	*30.4*

Table 5.2 – *Efficiency* sub-factors for each group in both scenarios

Table 5.2 shows the *duration*, *effort*, and *speed* scores for the groups in both scenarios. To find out the strength of the relationship between these three *Efficiency* sub-factors, a correlation test is carried out for each condition.

Results from the correlation test show the following:

Co-located

There is a **strong** correlation between *duration* (mean= 5:17, sd= 2:13) and *effort* (mean= 145, sd= 40.7) in the co-located scenario. $r = 0.82$, $p \leq 0.05$, $n = 15$, $R^2 = 0.67$, (95% confidence interval: 0.54, 0.94).

There is a **strong** negative correlation between *duration* (mean= 5:17, sd= 2:13) and *speed* (mean= 26.9, sd= 6.3) in the co-located scenario. $r = -0.75$, $p \leq 0.05$, $n = 15$, $R^2 = 0.56$, (95% confidence interval: -0.90, -0.38).

There is a weak negative correlation between *effort* (mean= 145, sd= 40.7) and *speed* (mean= 26.9, sd= 6.3) in the co-located scenario. $r = -0.29$, $p > 0.05$, $n = 15$, $R^2 = 0.08$, (95% confidence interval: -0.70, 0.26).

Table 5.3 and Figure 5.4 illustrate these relationships among *Efficiency* sub-factors. Table 5.4 shows another interpretation that takes the correlation coefficient a further step by presenting the *coefficient of determination (R^2)* matrix [41]. R^2 is interpreted as the variability shared between the variables. For example, the coefficient of determination between *duration* and *effort* shows that the correlation can explain 67% of the variability shared between the two variables.

	Duration	***Effort***	***Speed***
Duration	1.0	0.82	-0.75
Effort	0.82	1.0	-0.29
Speed	-0.75	-0.29	1.0

Table 5.3 – *Efficiency* sub-factors r-coefficients in co-located scenario

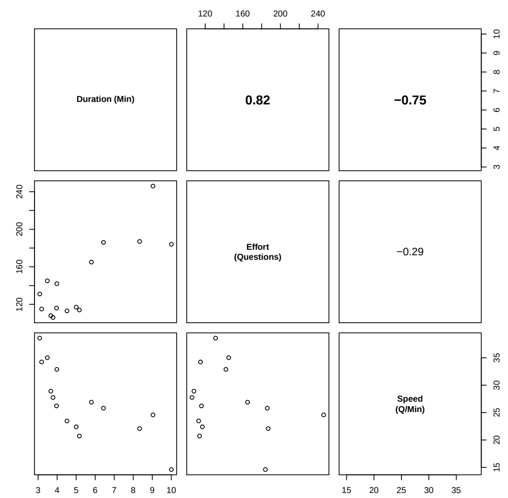


Figure 5.4 – *Efficiency* sub-factors correlation in co-located scenario

	Duration	***Effort***	***Speed***
Duration	1.0	0.67	0.56
Effort	0.67	1.0	0.08
Speed	0.56	0.08	1.0

Table 5.4 – *Efficiency* coefficient of determination in co-located scenario

Distributed

There is a **strong** correlation between *duration* (mean= 6:22, sd= 2:33) and *effort* (mean= 212.1, sd= 71.8) in the distributed scenario. $r = 0.89$, $p \leq 0.05$, $n = 15$, $R^2 = 0.79$, (95% confidence interval: 0.70, 0.96).

There is a **strong** negative correlation between *duration* (mean= 5:17, sd= 2:13) and *speed* (mean= 30.4, sd= 6.7) in the distributed scenario. $r = -0.62$, $p \leq 0.05$, $n = 15$, $R^2 = 0.38$, (95% confidence interval: -0.86, -0.16).

There is a weak negative correlation between *effort* (mean= 212.1, sd= 71.8) and *speed* (mean= 30.4, sd= 6.7) in the distributed scenario. $r = -0.28$, $p > 0.05$, $n = 15$, $R^2 = 0.08$, (95% confidence interval: -0.69, 0.27).

Table 5.5 and Figure 5.5 illustrate these relationships among *Efficiency* sub-factors in the distributed condition, as well as the *coefficient of determination* matrix in Table 5.6. The interpretation of these results exactly follow the co-located scenario.

	Duration	***Effort***	***Speed***
Duration	1.0	0.89	-0.62
Effort	0.89	1.0	-0.28
Speed	-0.62	-0.28	1.0

Table 5.5 – *Efficiency* sub-factors r-coefficients in distributed scenario

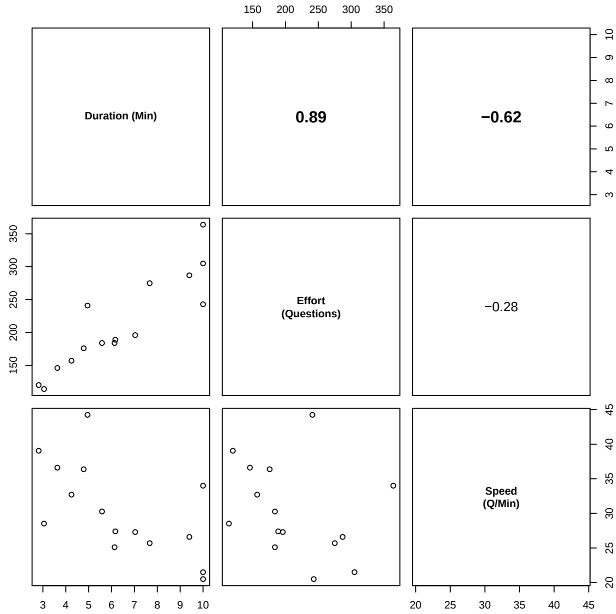


Figure 5.5 – *Efficiency* sub-factors correlation in distributed scenario

	Duration	*Effort*	*Speed*
Duration	1.0	0.79	0.38
Effort	0.79	1.0	0.08
Speed	0.38	0.08	1.0

Table 5.6 – *Efficiency* coefficient of determination in distributed scenario

Comparison

To put correlation findings in perspective, the r-coefficients in both scenarios are compared. Only the correlations that are statistically significant in co-located, distributed, or both are compared. Table 5.7 summarises the r-coefficients in both conditions.

	Co-located	**Distributed**
Duration / Effort	0.82	0.89
Duration / Speed	-0.75	-0.62

Table 5.7 – *Efficiency* r-coefficient that are statistically significant

Fisher's z-Transformation [26] test is applied on the correlation coefficients shown in Table 5.7 to find out the significance of the differences between the coefficients in the two different scenarios. The results of the test are:

> Fisher's z-Transformation test was conducted to compare the correlation coefficients between *duration* and *effort* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 0.65$, $p > 0.05$.
>
> Fisher's z-Transformation test was conducted to compare the correlation coefficients between *duration* and *speed* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 0.61$, $p > 0.05$.

A summary of the results presented in this section are given in Section 6.2

5.2.2 Accuracy

Accuracy is a measurement of how precise and effective are the results generated by the participants in a given task. *Accuracy* describes the state in which a system or the user makes error [78]. A frequently used measure of *Accuracy* is the error rate, which measures the ratio of errors during the lapse of the given task.

In this research, the requested result is to visit all the graph nodes by traversing the quickest needed links. As shown previously in Chapter 4, links can be traversed by solving questions assigned to them, and only correct answers will cause progress through the graph. The sub-factors that are taken into consideration when studying *Accuracy* are:

Incorrectness ratio: Ratio of incorrect answers to the total answers a group has given, per minute.

Added Difficulty ratio: Ratio of the added weight of the resulted graph over the minimal spanning tree to the weight of the minimal spanning tree (MST= 24), per minute.

Unnecessary Work ratio: Ratio of the time spent on working on unnecessary links to the total links time, per minute.

Sub-factor	Scenario	Mean	Median	SD	Min	Max
Incorrectness ratio (%)	**Co-located**	1.6	1.4	1.1	0.2	4.6
	Distributed	2.0	1.8	1.1	0.2	3.9
Added Difficulty ratio (%)	**Co-located**	3.5	2.5	2.7	0.0	7.9
	Distributed	4.1	4.4	2.3	0.0	8.0
Unnecessary Work ratio (%)	**Co-located**	4.4	3.6	3.3	0.0	11.2
	Distributed	5.5	5.3	3.1	1.6	12.6

Table 5.8 – Basic descriptive results for *Accuracy* sub-factors

5.2.2.1 Basic descriptive findings

In this subsection, the basic descriptive statistical findings are presented in Table 5.8 for the three aforementioned sub-factors of *Accuracy: incorrectness, added difficulty,* and *unnecessary work* in the two conditions.

5.2.2.2 Investigating differences

Incorrectness ratio

Hypothesis P.4: *There is no difference between the means of incorrectness ratio in the two conditions.*

A paired-samples t-test was conducted to compare the *incorrectness ratio* in the co-located and distributed conditions. There was no significant difference in the scores of the *incorrectness ratio* for the co-located and distributed conditions; $t(14) = -1.45$, $p > 0.05$, (95% confidence interval: -1.1%, 0.2%). Figure 5.6 illustrates the *incorrectness ratio* differences between the two conditions for all the groups.

Hypothesis **P.4** test: **Fail to Reject**.

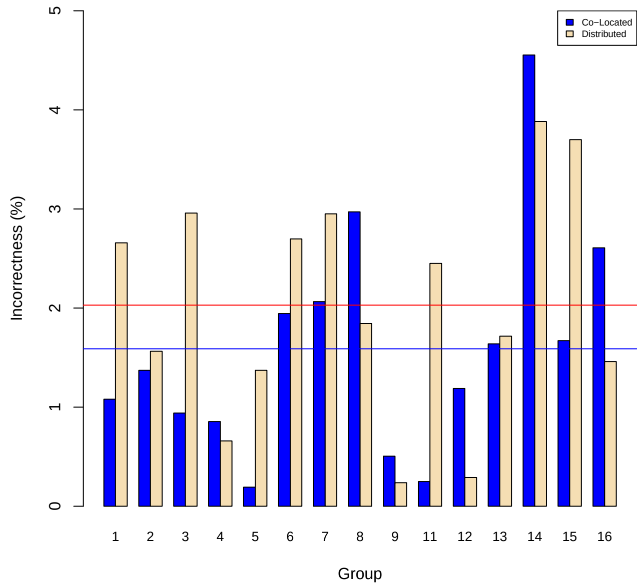


Figure 5.6 – *Incorrectness ratio* differences between the two conditions

Added difficulty ratio

Hypothesis P.5: *There is no difference between the means of added difficulty ratio in the two conditions.*

A paired-samples t-test was conducted to compare the *added difficulty ratio* in the co-located and distributed conditions. There was no significant difference in the scores of the *added difficulty ratio* for the co-located and distributed conditions; $t(14) = -0.77$, $p > 0.05$, (95% confidence interval: -2.5%, 1.17%). Figure 5.7 illustrates the *added difficulty ratio* differences between the two conditions for all the groups.

Hypothesis **P.5** test: **Fail to Reject**.

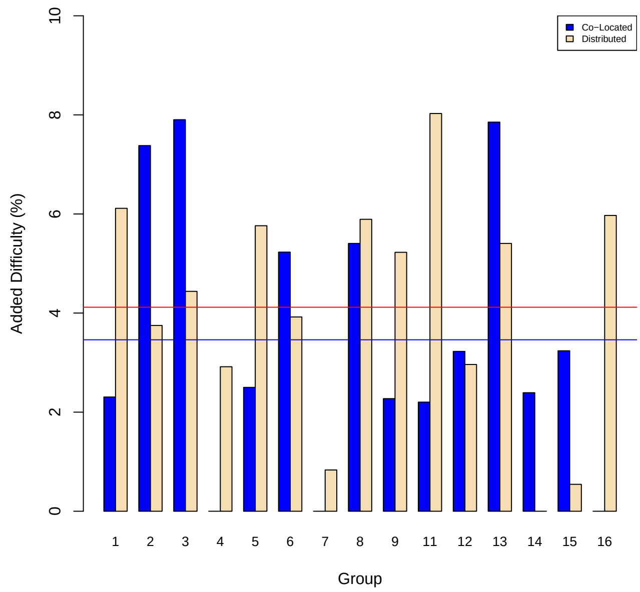


Figure 5.7 – *Added Difficulty ratio* differences between the two conditions

Unnecessary work ratio

> ***Hypothesis P.6***: *There is no difference between the means of unnecessary work ratio in the two conditions.*
>
> A paired-samples t-test was conducted to compare the *unnecessary work ratio* in the co-located and distributed conditions. There was no significant difference in the scores of the *unnecessary work ratio* for the co-located and distributed conditions; $t(14) = -0.87$, $p > 0.05$, (95% confidence interval: -3.8%, 1.6%). Figure 5.8 illustrates the *unnecessary work ratio* differences between the two conditions for all the groups.
>
> Hypothesis **P.6** test: **Fail to Reject**.

5.2.2.3 Sub-factors correlation

Table 5.9 shows the scores of the *Accuracy* underlying sub-factors (*incorrectness ratio*, *added difficulty ratio*, and *unnecessary work ratio*) for the 15 groups in both scenarios.

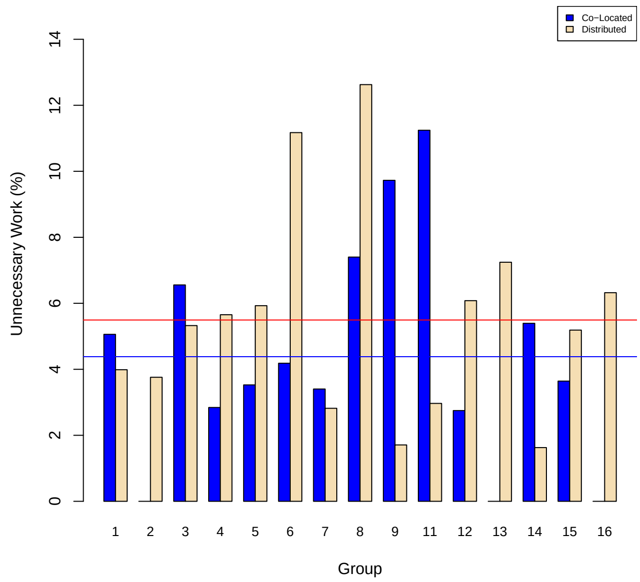


Figure 5.8 – *Unnecessary Work ratio* differences between the two conditions

These scores are used to study the relationship strength among the sub-factors which shall aid in understanding the internal interactions in the *Accuracy* area. To find out these relationships, a correlation test is carried out for each condition (co-located and distributed). With the exception of *Incorrectness* and *Added Difficulty* relationship in distributed scenario, the test shows, generally, a very weak to weak relationships among *Accuracy* sub-factors in both scenarios. The following are the formal detailed results of the tests for both conditions.

Co-located

Results from the correlation test shows that there is a negative very weak (almost negligible) to weak relationship among the sub-factors of *Accuracy* in the co-located scenario. Table 5.10 and Figure 5.9 show these correlation test results. Table 5.11 shows the *coefficient of determination (R^2)* matrix, which presents the variability shared between the variables [41]. For example, the coefficient of determination between *incorrectness ratio* and *unnecessary work ratio* shows that the correlation can explain only 4% of the variability shared between the two variables. Formally, the results are:

	Co-Located			**Distributed**		
Group ID	**Incorrectness ratio (%)**	**Added Difficulty ratio (%)**	**Unnecessary Work ratio (%)**	**Incorrectness ratio (%)**	**Added Difficulty ratio (%)**	**Unnecessary Work ratio (%)**
1	1.1	2.3	5.1	2.7	6.1	4.0
2	1.4	7.4	0.0	1.6	3.8	3.8
3	0.9	7.9	6.6	3.0	4.4	5.3
4	0.9	0.0	2.8	0.7	2.9	5.7
5	0.2	2.5	3.5	1.4	5.8	5.9
6	1.9	5.2	4.2	2.7	3.9	11.2
7	2.1	0.0	3.4	3.0	0.8	2.8
8	3.0	5.4	7.4	1.8	5.9	12.6
9	0.5	2.3	9.7	0.2	5.2	1.7
11	0.2	2.2	11.2	2.5	8.0	3.0
12	1.2	3.2	2.7	0.3	3.0	6.1
13	1.6	7.9	0.0	1.7	5.4	7.2
14	4.6	2.4	5.4	3.9	0.0	1.6
15	1.7	3.2	3.6	3.7	0.5	5.2
16	2.6	0.0	0.0	1.5	6.0	6.3
mean	*1.6*	*3.5*	*4.4*	*2.0*	*4.1*	*5.5*

Table 5.9 – *Accuracy* sub-factors for each group in both scenarios

There is a very weak negative correlation between *incorrectness ratio* (mean= 1.6%, sd= 1.1%) and *added difficulty ratio* (mean= 3.5%, sd= 2.7%) in the co-located scenario. $r = -0.02$, $p > 0.05$, $n = 15$, $R^2 = 0.00$, (95% confidence interval: -0.53, 0.49).

There is a weak negative correlation between *incorrectness ratio* (mean= 1.6%, sd= 1.1%) and *unnecessary work ratio* (mean= 4.4%, sd= 3.3%) in the co-located scenario. $r = -0.20$, $p > 0.05$, $n = 15$, $R^2 = 0.04$, (95% confidence interval: -0.65, 0.34).

	Incorrectness ratio	***Added Difficulty ratio***	***Unnecessary Work ratio***
Incorrectness ratio	1.00	-0.02	-0.20
Added Difficulty ratio	-0.02	1.00	-0.10
Unnecessary Work ratio	-0.20	-0.10	1.00

Table 5.10 – *Accuracy* sub-factors r-coefficients in co-located scenario

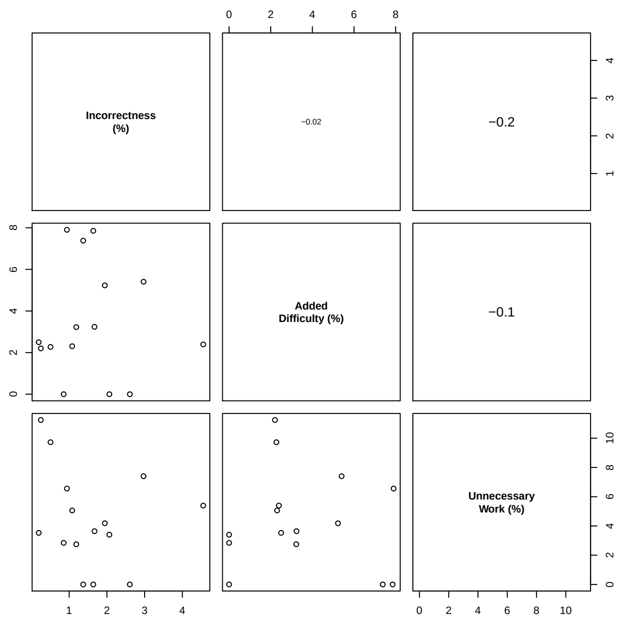


Figure 5.9 – *Accuracy* sub-factors correlation in co-located scenario

There is a weak correlation between *added difficulty ratio* (mean= 3.5%, sd= 2.7%) and *unnecessary work ratio* (mean= 4.4%, sd= 3.3%) in the co-located scenario. $r = -0.10$, $p > 0.05$, $n = 15$, $R^2 = 0.01$, (95% confidence interval: -0.58, 0.43).

	Incorrectness ratio	***Added Difficulty ratio***	***Unnecessary Work ratio***
Incorrectness ratio	1.00	0.00	0.04
Added Difficulty ratio	0.00	1.00	0.01
Unnecessary Work ratio	0.04	0.01	1.00

Table 5.11 – *Accuracy* coefficient of determination in co-located scenario

	Incorrectness ratio	***Added Difficulty ratio***	***Unnecessary Work ratio***
Incorrectness ratio	1.00	-0.40	-0.10
Added Difficulty ratio	-0.40	1.00	0.24
Unnecessary Work ratio	-0.10	0.24	1.00

Table 5.12 – *Accuracy* sub-factors r-coefficients in distributed scenario

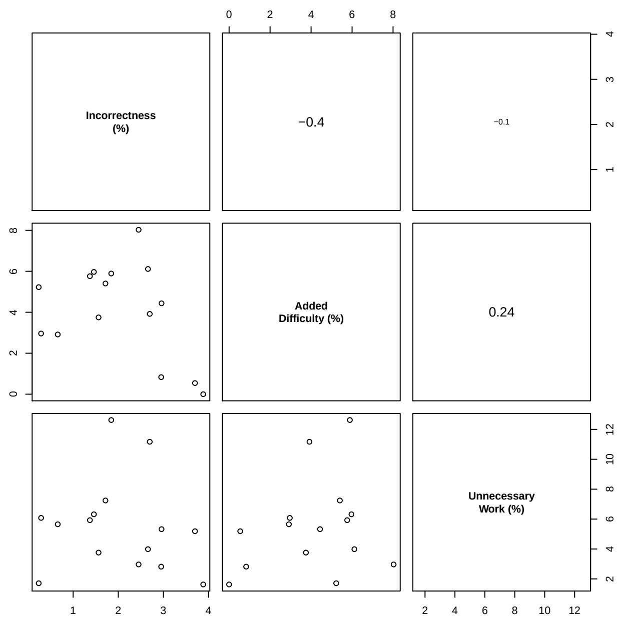


Figure 5.10 – *Accuracy* sub-factors correlation in distributed scenario

Distributed

The correlation coefficients in the distributed scenario show slightly stronger relationships among the *Accuracy* sub-factors than their counterparts in the co-located scenario. The reason for this difference is discussed in Subsection 6.2.2. Table 5.12 and Figure 5.10 illustrate the correlations among the *Accuracy* underlying sub-factors in the distributed scenario, and are presented as coefficient of determination in Table 5.13. Results can be interpreted exactly the same way as in the co-located scenario.

The formal interpretation of the above correlation test is:

	Incorrectness ratio	**Added Difficulty ratio**	**Unnecessary Work ratio**
Incorrectness ratio	1.00	0.16	0.01
Added Difficulty ratio	0.16	1.00	0.06
Unnecessary Work ratio	0.01	0.06	1.00

Table 5.13 – *Accuracy* coefficient of determination in distributed scenario

There is a moderate negative correlation between *incorrectness ratio* (mean= 2.0%, sd= 1.1%) and *added difficulty ratio* (mean= 4.1%, sd= 2.3%) in the distributed scenario. $r = -0.40$, $p > 0.05$, $n = 15$, $R^2 = 0.16$, (95% confidence interval: -0.75, 0.15).

There is a weak negative correlation between *incorrectness ratio* (mean= 2.0%, sd= 1.1%) and *unnecessary work ratio* (mean= 5.5%, sd= 3.1%) in the distributed scenario. $r = -0.10$, $p > 0.05$, $n = 15$, $R^2 = 0.01$, (95% confidence interval: -0.60, 0.44).

There is a weak correlation between *added difficulty ratio* (mean= 4.1%, sd= 2.3%) and *unnecessary work ratio* (mean= 5.5%, sd= 3.1%) in the distributed scenario. $r = 0.24$, $p > 0.05$, $n = 15$, $R^2 = 0.26$, (95% confidence interval: -0.31, 0.67).

Comparison

Findings of correlation analysis of *Accuracy* sub-factors show that none of those correlations is statistically significant, hence, the comparison between coefficients is not carried out.

5.2.3 Performance factors correlation

In subsections 5.2.1 and 5.2.2, the PERFORMANCE aspects of *Efficiency* and *Accuracy* have been analysed on their own with their internal sub-factors interactions. To complete the PERFORMANCE analysis, this subsection shall present the correlation between these aspects to study their effect on each other, then compare the outcomes in both scenarios of the study, the co-located and the distributed conditions. This will help in understanding

	Duration	**Effort**	**Speed**	**Incorrectness ratio**	**Added Difficulty ratio**	**Unnecessary Work ratio**
Duration	1	0.82	-0.75	-0.29	-0.34	-0.12
Effort	0.82	1	-0.29	-0.03	-0.13	0
Speed	-0.75	-0.29	1	0.47	0.46	0.26
Incorrectness ratio	-0.29	-0.03	0.47	1	-0.02	-0.2
Added Difficulty ratio	-0.34	-0.13	0.46	-0.02	1	-0.1
Unnecessary Work ratio	-0.12	0	0.26	-0.2	-0.1	1

Table 5.14 – PERFORMANCE sub-factors r-coefficients in co-located scenario

the high level construct from the PERFORMANCE side, which will be useful when studying other parts of the research later.

5.2.3.1 Co-located

Looking into the details of correlation among all sub-factors will give a deeper understanding of the internal relationships between PERFORMANCE components in co-located scenario. Table 5.14 and Figure 5.11 illustrate the correlation coefficients of all sub-factors along with detailed correlation plot matrix. Table 5.15 presents the results of coefficient of determination to give the result a more meaningful interpretation.

Only the correlations between the sub-factors in the different areas, i.e. *Efficiency* and *Accuracy*, are of interest at this stage; the internal correlations between sub-factors of each specific area has been studied in the previous subsections (see subsections 5.2.1.3 and 5.2.2.3). Below are the formal results of this test. To make phrasing the results easier, Table 5.16 presents all the sub-factors mean and standard deviation scores that should accompany the correlation test results.

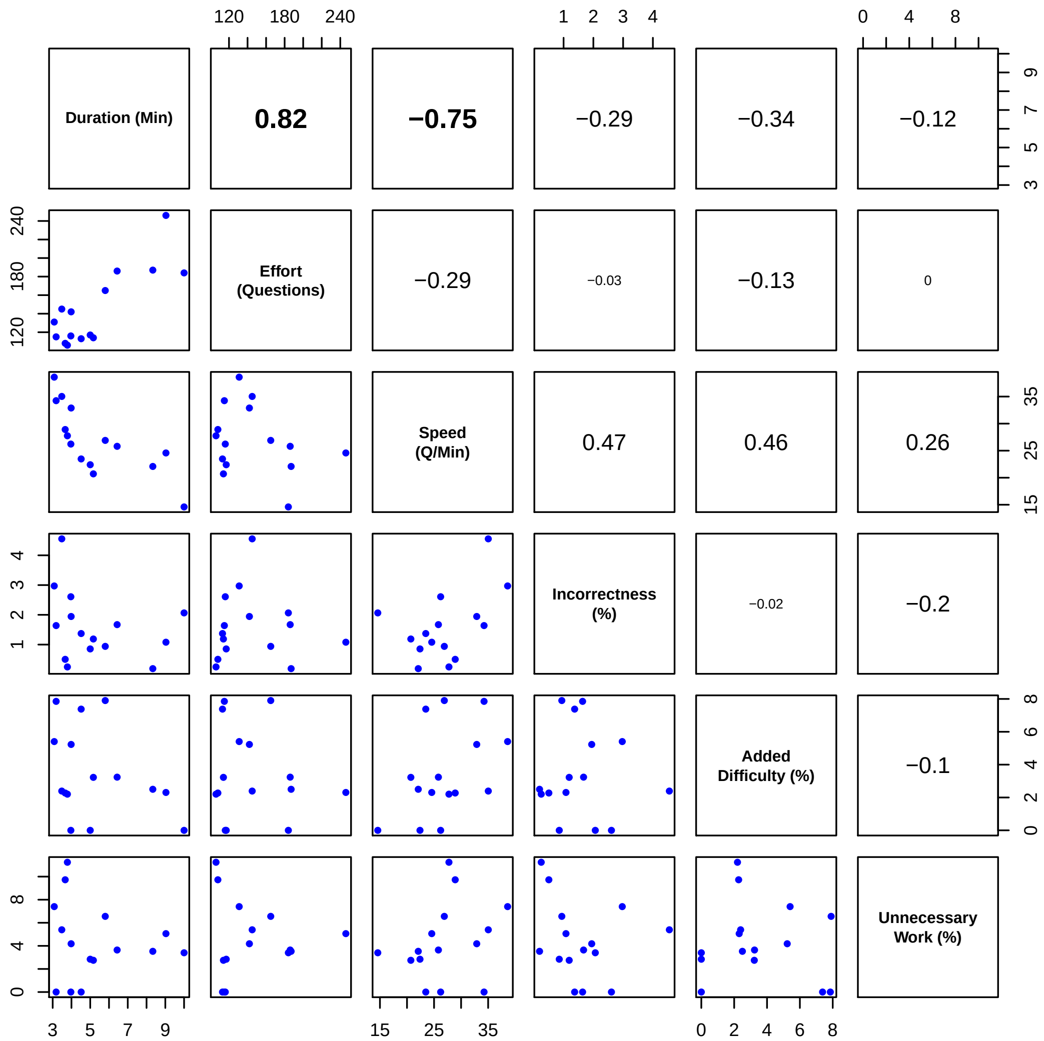


Figure 5.11 – PERFORMANCE sub-factors correlation in co-located scenario

There is a weak negative correlation between *duration* and *incorrectness ratio* in the co-located scenario. $r = -0.29$, $p > 0.05$, $n = 15$, $R^2 = 0.08$, (95% confidence interval: -0.77, 0.26).

There is a moderate negative correlation between *duration* and *added difficulty ratio* in the co-located scenario. $r = -0.34$, $p > 0.05$, $n = 15$, $R^2 = 0.12$, (95% confidence interval: -0.73, 0.20).

	Duration	*Effort*	*Speed*	*Incorrectness ratio*	*Added Difficulty ratio*	*Unnecessary Work ratio*
Duration	1	0.67	0.56	0.08	0.12	0.01
Effort	0.67	1	0.08	0	0.02	0
Speed	0.56	0.08	1	0.22	0.21	0.07
Incorrectness ratio	0.08	0	0.22	1	0	0.04
Added Difficulty ratio	0.12	0.02	0.21	0	1	0.01
Unnecessary Work ratio	0.01	0	0.07	0.04	0.01	1

Table 5.15 – PERFORMANCE sub-factors coefficient of determination in co-located scenario

	Mean	**SD**
Duration **(m:s)**	5:17	2:13
Effort **(Questions)**	145	40.7
Speed **(Q/Min)**	26.9	6.3
Incorrectness ratio **(%)**	1.6	1.5
Added Difficulty ratio **(%)**	3.5	2.7
Unnecessary Work ratio **(%)**	4.4	3.3

Table 5.16 – PERFORMANCE sub-factors mean and standard deviation in co-located scenario

There is a weak negative correlation between *duration* and *unnecessary work ratio* in the co-located scenario. $r = -0.12$, $p > 0.05$, $n = 15$, $R^2 = 0.01$, (95% confidence interval: -0.60, 0.42).

There is a weak negative correlation between *effort* and *incorrectness ratio* in the co-located scenario. $r = -0.03$, $p > 0.05$, $n = 15$, $R^2 = 0.0$, (95% confidence interval: -0.53, 0.49).

There is a weak negative correlation between *effort* and *added difficulty ratio* in the co-located scenario. $r = -0.13$, $p > 0.05$, $n = 15$, $R^2 = 0.02$, (95% confidence interval: -0.60, 0.41).

There is no correlation between *effort* and *unnecessary work ratio* in the co-located scenario. $r = 0.00$, $p > 0.05$, $n = 15$, $R^2 = 0.0$, (95% confidence interval: -0.51, 0.51).

There is a moderate correlation between *speed* and *incorrectness ratio* in the co-located scenario. $r = 0.47$, $p > 0.05$, $n = 15$, $R^2 = 0.22$, (95% confidence interval: -0.06, 0.79).

There is a moderate correlation between *speed* and *added difficulty ratio* in the co-located scenario. $r = 0.46$, $p > 0.05$, $n = 15$, $R^2 = 0.21$, (95% confidence interval: -0.07, 0.79).

There is a weak correlation between *speed* and *unnecessary work ratio* in the co-located scenario. $r = 0.26$, $p > 0.05$, $n = 15$, $R^2 = 0.07$, (95% confidence interval: -0.29, 0.68).

5.2.3.2 Distributed

Correlation between all the sub-factors of PERFORMANCE in the distributed scenario is also tested to give a deeper understanding of the internal relationships between different components. Table 5.17 and Figure 5.12 illustrate the correlation coefficients of all sub-factors along with detailed plot matrix. Coefficient of determination matrix is presented in Table 5.18 as well.

As in the co-located scenario, only the correlations between the sub-factors in the different areas are of interest at this stage; the internal correlations between sub-factors of each specific area has been studied previously in Subsection 5.2.1.3 and Subsection 5.2.2.3. Below are the formal results of this test, and Table 5.19 presents all the sub-factors mean and standard deviation scores as well, so no need to state them with every single result.

There is a moderate negative correlation between *duration* and *incorrectness ratio* in the distributed scenario. $r = -0.35$, $p > 0.05$, $n = 15$, $R^2 = 0.12$, (95% confidence interval: -0.71, 0.24).

There is a weak negative correlation between *duration* and *added difficulty ratio* in the distributed scenario. $r = -0.27$, $p > 0.05$, $n = 15$, $R^2 = 0.07$, (95% confidence interval: -0.69, 0.28).

	Duration	***Effort***	***Speed***	***Incorrectness ratio***	***Added Difficulty ratio***	***Unnecessary Work ratio***
Duration	1	0.89	-0.62	-0.35	-0.27	-0.09
Effort	0.89	1	-0.28	-0.30	-0.25	0.09
Speed	-0.62	-0.28	1	0.16	0.43	0.42
Incorrectness ratio	-0.35	-0.30	0.16	1	-0.40	-0.10
Added Difficulty ratio	-0.27	-0.25	0.43	-0.40	1	0.24
Unnecessary Work ratio	-0.09	0.09	0.42	-0.10	0.24	1

Table 5.17 – PERFORMANCE sub-factors r-coefficients in distributed scenario

	Duration	***Effort***	***Speed***	***Incorrectness ratio***	***Added Difficulty ratio***	***Unnecessary Work ratio***
Duration	1	0.79	0.38	0.12	0.07	0.01
Effort	0.79	1	0.08	0.09	0.06	0.01
Speed	0.38	0.08	1	0.03	0.18	0.18
Incorrectness ratio	0.12	0.09	0.03	1	0.16	0.01
Added Difficulty ratio	0.07	0.06	0.18	0.16	1	0.06
Unnecessary Work ratio	0.01	0.01	0.18	0.01	0.06	1

Table 5.18 – PERFORMANCE sub-factors coefficient of determination in distributed scenario

There is a weak negative correlation between *duration* and *unnecessary work ratio* in the distributed scenario. $r = -0.09$, $p > 0.05$, $n = 15$, $R^2 = 0.01$, (95% confidence interval: -0.58, 0.44).

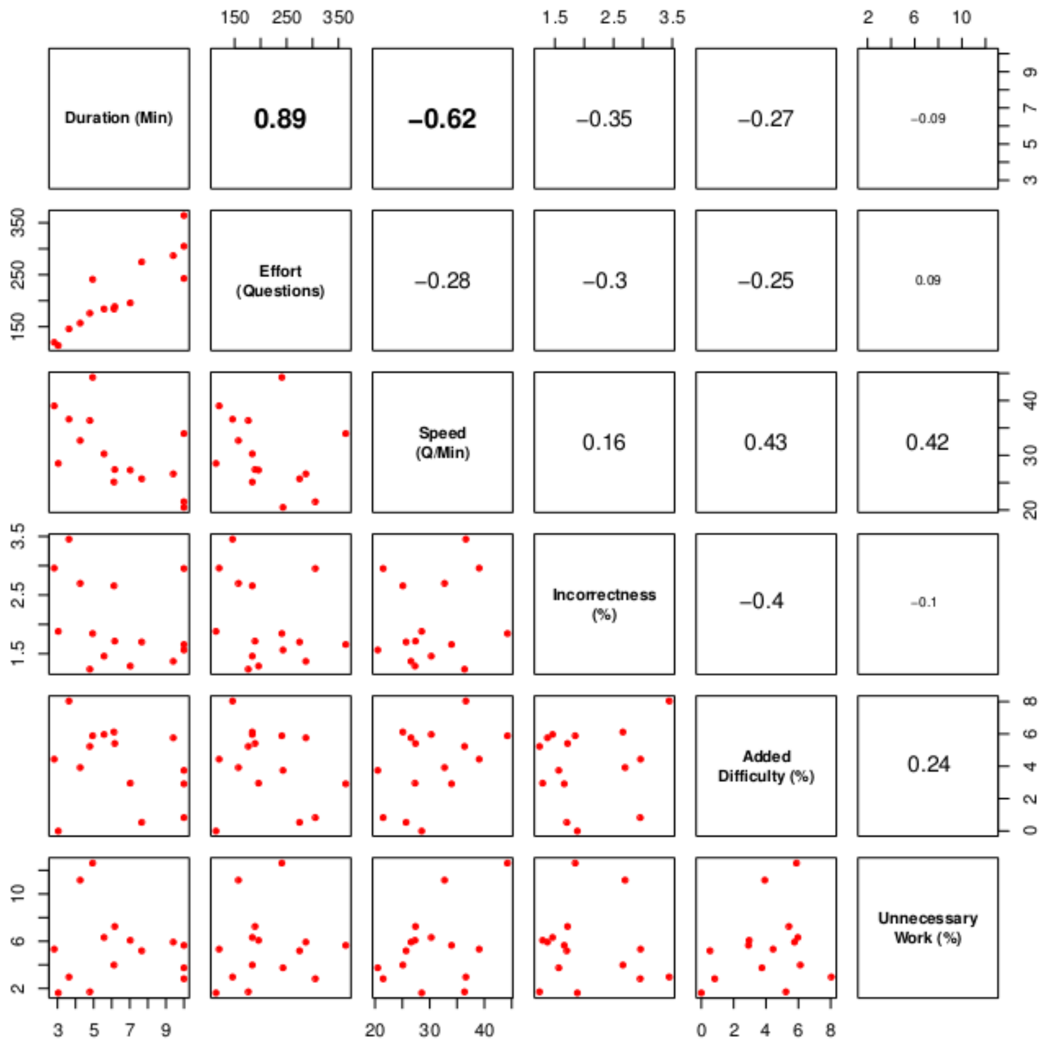


Figure 5.12 – PERFORMANCE sub-factors correlation in distributed scenario

There is a weak negative correlation between *effort* and *incorrectness ratio* in the distributed scenario. $r = -0.30$, $p > 0.05$, $n = 15$, $R^2 = 0.09$, (95% confidence interval: -0.69, 0.27).

There is a moderate negative correlation between *effort* and *added difficulty ratio* in the distributed scenario. $r = -0.25$, $p > 0.05$, $n = 15$, $R^2 = 0.06$, (95% confidence interval: -0.67, 0.30).

	Mean	SD
Duration **(m:s)**	6:22	2:33
Effort **(Questions)**	212.1	71.8
Speed **(Q/Min)**	30.4	6.7
Incorrectness ratio **(%)**	2.0	1.1
Added Difficulty ratio **(%)**	4.1	2.3
Unnecessary Work ratio **(%)**	5.5	3.1

Table 5.19 – PERFORMANCE sub-factors mean and standard deviation in distributed scenario

There is a weak correlation between *effort* and *unnecessary work ratio* in the distributed scenario. $r = 0.09$, $p > 0.05$, $n = 15$, $R^2 = 0.01$, (95% confidence interval: -0.44, 0.58).

There is a weak correlation between *speed* and *incorrectness ratio* in the distributed scenario. $r = 0.16$, $p > 0.05$, $n = 15$, $R^2 = 0.03$, (95% confidence interval: -0.61, 0.40).

There is a moderate correlation between *speed* and *added difficulty ratio* in the distributed scenario. $r = 0.43$, $p > 0.05$, $n = 15$, $R^2 = 0.18$, (95% confidence interval: -0.10, 0.77).

There is moderate correlation between *speed* and *unnecessary work ratio* in the distributed scenario. $r = 0.42$, $p > 0.05$, $n = 15$, $R^2 = 0.17$, (95% confidence interval: -0.12, 0.77).

5.2.3.3 Comparison

In comparing the interrelationships of *Efficiency* and *Accuracy* areas, Fisher's z-Transformation test is used in this research (see Subsection 3.2.4). The test is applied on the correlation coefficients found previously to find out the significance of differences between the coefficients in the two different scenarios. This is formulated in the following hypothesis, with a detailed discussion in Subsection 6.2.3.

Hypothesis P.7: *There is no difference between the correlation coefficients among performance sub-factors in the two conditions.*

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *duration* and *incorrectness ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 0.05$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *duration* and *added difficulty ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 0.19$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *duration* and *unnecessary work ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 0.07$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *effort* and *incorrectness ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 0.63$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *effort* and *added difficulty ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 0.31$, $p > 0.05$.

continued...

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *effort* and *unnecessary work ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 0.22$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *speed* and *incorrectness ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 1.59$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *speed* and *added difficulty ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 0.09$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *speed* and *unnecessary work ratio* in co-located and distributed conditions. There was no significant difference in the coefficients scores for co-located and distributed conditions; $z(15) = 0.44$, $p > 0.05$.

Hypothesis **P.7** test: **Fail to Reject**.

5.2.4 Summary

In this section (Group Performance), the results related to PERFORMANCE has been presented and analysed. The area of PERFORMANCE is divided into two sub-areas: *Efficiency* and *Accuracy*. For each sub-area, the study findings has been compared for the two conditions, co-located and distributed to find out whether there are significant differences. Then a correlation test has been carried out to find out the strength of relationships among the sub-factors in each area in both conditions. Finally, a correlation test among all the sub-factors of PERFORMANCE has been carried out with comparison between the two conditions. A detailed discussion of these results is in Section 6.2.

5.3 Group Members Collaboration

Group COLLABORATION during their work on the given task is studied and analysed as a result of the experimental work of this study. Collaboration is a significant aspect to consider in modern human-computer interaction, especially when studying multi-touch surfaces as they naturally encourage collaborative work [150, 113].

This research focuses on three major areas of COLLABORATION: *Styles*, *Communication*, and *Balance*. *Collaboration Styles* analyse the different styles of how the participants are collaborating together while they work on the given task (see Subsection 5.3.1). *Communication* is the analysis of messages exchanged between the participants during the task (see Subsection 5.3.2). And *Contribution Balance* analyses the share of work and communication that each participant has given to the task (see Subsection 5.3.3). The related results of these areas shall be presented in this section; with investigation of differences in both conditions, co-located and distributed.

System logs and video recordings are used as the data source for this part of the analysis. Differences between the two experimental conditions, co-located and distributed, are investigated using the *paired-samples t-test* statistical method (see Subsection 3.2.3) to calculate the significance of the difference in means. The reliability of the results is considered in a 95% confidence interval. The Gini Coefficient method is used to study the contribution balance as explained in Subsection 3.2.5.

5.3.1 Collaboration styles

As participants worked on the given task, they adopted different collaboration styles. For example, they might work on the same part of the problem at the same time; at other times, they would separate to work on different parts of the general problem. This flexibility allowed them to plan their own strategy and solution to the problem. These styles are coded based on the participants interactions and with the game and with each other. That will help in understanding which information and views of the game space participants were sharing and collaborating on at a given moment. The styles and codes are based on Isenberg work on the collaboration styles [64]. Isenberg identified eight general collaboration styles used to analyse the collaborative work in shared work spaces. Those styles were explained in more details in Chapter 2. Only the styles that have been noticed in the experiment were analysed in this research. The other styles are not used because they are inapplicable to this study. The *Collaboration Styles* used in this research are:

Communicating for Help (CH): When the participants are communicating to assist each other. This is an adaptation of the original DISC style proposed by Isenberg [64].

View Engaged (VE): When one of the participants is not actively working on the task but he/she is engaged in watching what the other participant is doing.

Same General Problem (SGP): When both participants are working at the same time on the task but on different links.

Same Specific Problem (SSP): When both participants are working at the same time on the same link.

All of these styles are calculated as a time ratio of the duration of the game. *Collaboration Styles* are further grouped into two categories: Close and Loose [64]. Close collaboration is generally characterised by active communication for assistance and engagement in the same task by both participants. However, in loose collaboration, communication and engagement is not noticed as much. In this study, the *SGP* style is considered loose, while *CH*, *VE*, and *SSP* style are considered close.

To find out these *Styles* and their effect on the COLLABORATION work for each group, this research used the data extracted from system logs and video recordings of experiment sessions as explained previously in Chapter 3.

5.3.1.1 Basic descriptive findings

In this subsection, the basic descriptive statistical findings are presented in Table 5.20 for the four aforementioned sub-factors of *Collaboration Styles*: *CH*, *VE*, *SGP*, and *SSP* in the two conditions.

Style	Scenario	Mean	Median	SD	Min	Max
CH (%)	**Co-located**	10.2	8.8	6.1	0.4	24.8
	Distributed	6.8	5.4	5.0	0.0	16.8
VE (%)	**Co-located**	8.9	7.9	6.4	0.5	21.6
	Distributed	5.5	4.5	3.9	0.0	13.5
SGP (%)	**Co-located**	53.1	55.0	13.6	26.7	70.3
	Distributed	70.4	69.3	12.6	46.2	90.2
SSP (%)	**Co-located**	27.8	25.9	13.7	7.3	66.7
	Distributed	24.1	23.3	12.3	6.7	47.8

Table 5.20 – Basic descriptive results for *Collaboration Styles*

5.3.1.2 Investigating differences

Communicating for Help (CH)

Hypothesis C.1: *There is no difference between the means of time spent in CH collaboration style in the two conditions.*

A paired-samples t-test was conducted to compare the time spent in *CH Collaboration Style* in the co-located and distributed conditions. There was no significant difference in the scores of time spent in *CH Collaboration Style* for the co-located and distributed conditions; $t(14) = 1.95$, $p > 0.05$, (95% confidence interval: -0.34, 7.14). Figure 5.13 illustrates the *CH collaboration style* differences between the two conditions for all the groups.

Hypothesis **C.1** test: **Fail to Reject**.

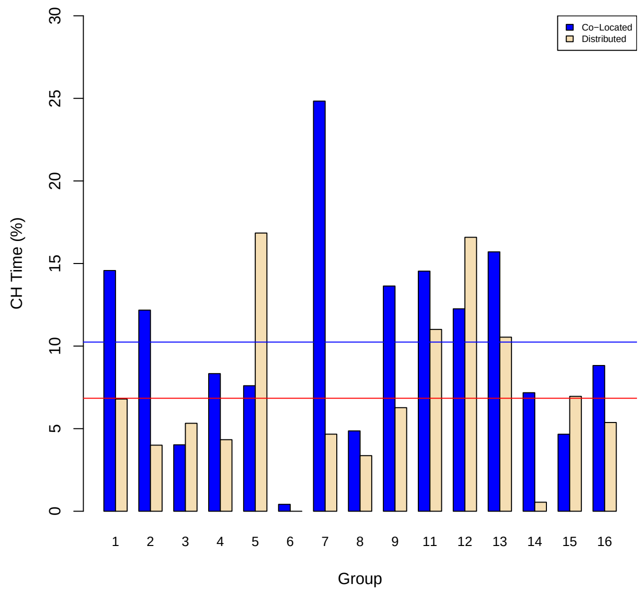


Figure 5.13 – *CH Collaboration Style* differences between the two conditions

View Engaged (VE)

Hypothesis C.2: *There is no difference between the means of time spent in VE collaboration style in the two conditions.*

A paired-samples t-test was conducted to compare the time spent in *VE Collaboration Style* in the co-located and distributed conditions. There was a **significant** difference in the scores of time spent in *VE Collaboration Style* for the co-located and distributed conditions; $t(14) = 2.53$, $p \leq 0.05$, (95% confidence interval: 0.53, 6.31). Figure 5.14 illustrates the *VE collaboration style* differences between the two conditions for all the groups.

Hypothesis **C.2** test: **Reject**.

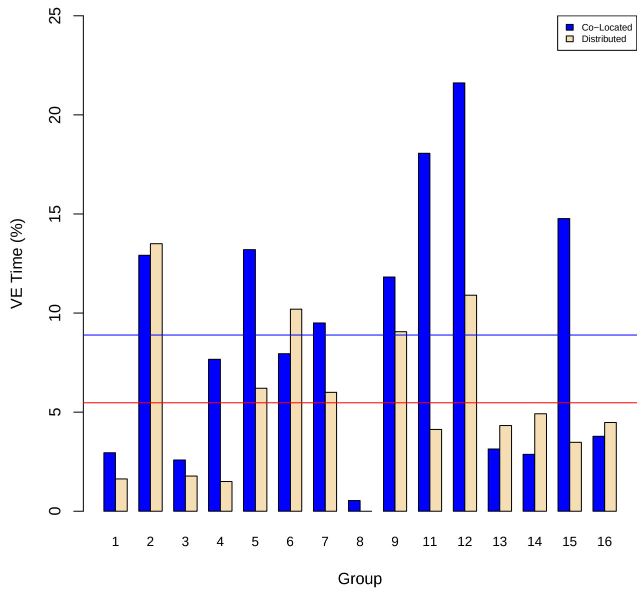


Figure 5.14 – *VE Collaboration Style* differences between the two conditions

Same General Problem (SGP)

Hypothesis C.3: *There is no difference between the means of time spent in SGP collaboration style in the two conditions.*

A paired-samples t-test was conducted to compare the time spent in *SGP Collaboration Style* in the co-located and distributed conditions. There was a **significant** difference in the scores of time spent in *SGP Collaboration Style* for the co-located and distributed conditions; $t(14) = -5.46$, $p \leq 0.05$, (95% confidence interval: -24.1, -10.51). Figure 5.15 illustrates the *SGP collaboration style* differences between the two conditions for all the groups.

Hypothesis **C.3** test: **Reject**.

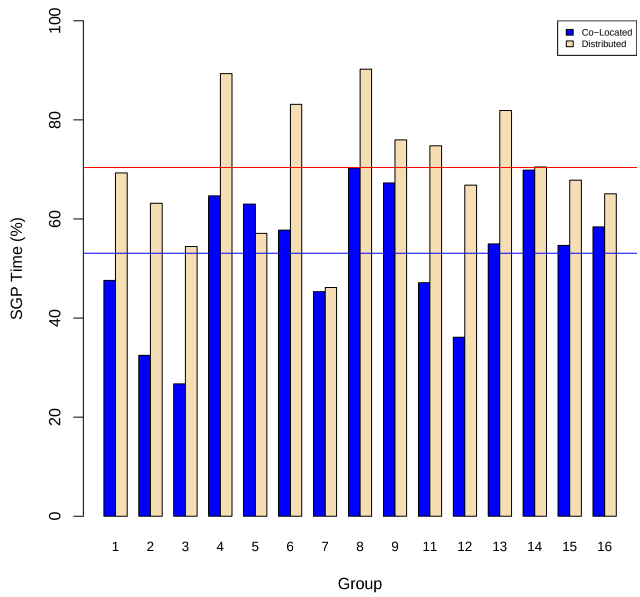


Figure 5.15 – *SGP Collaboration Style* differences between the two conditions

Same Specific Problem (SSP)

Hypothesis C.4: *There is no difference between the means of time spent in SSP collaboration style in the two conditions.*

A paired-samples t-test was conducted to compare the time spent in *SSP Collaboration Style* in the co-located and distributed conditions. There was no significant difference in the scores of time spent in *SSP Collaboration Style* for the co-located and distributed conditions; $t(14) = 0.92$, $p > 0.05$, (95% confidence interval: -4.81, 12.1). Figure 5.16 illustrates the *SSP collaboration style* differences between the two conditions for all the groups.

Hypothesis **C.4** test: **Fail to Reject**.

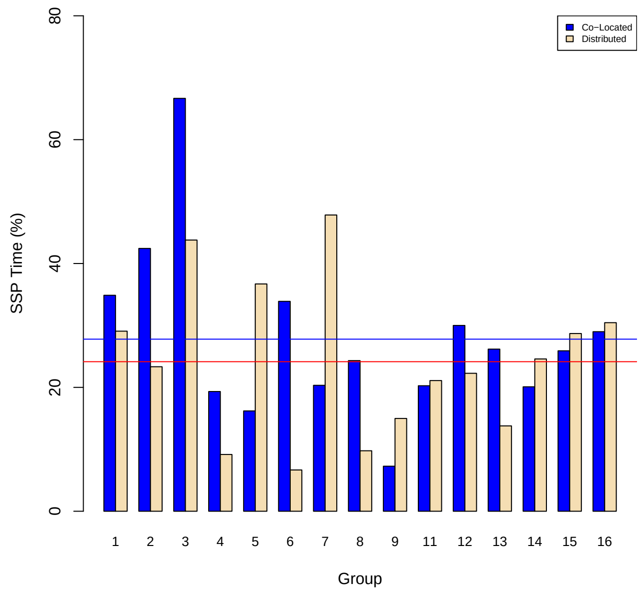


Figure 5.16 – *SSP Collaboration Style* differences between the two conditions

5.3.2 Players communication

Communication between participants has been noticed and recorded during their game playing sessions. The implemented game is a kind of CSCW system that needs direct communication between the users (players) [22, 32] to provide both of them the ability to ask for help or to offer help based on the progress they make and observe on the shared game workspace [147]. Communication is analysed in the two experimental conditions: *co-located*, where players were able to communicate verbally, and *distributed*, where players communicated via simple messaging mechanism (see Chapter 4 for more details). The *Communication* sub-factors that were considered in this research are:

Frequency: Number of total communication attempts (initiation and responding) *per minute*[3].

Start: Time of the first communication attempt as a *ratio* of the total game duration.

Interval: Time span from first communication attempt to the last one as a *ratio* to total game duration.

[3] Not to be mistaken for the term *"frequency"* used in radio and telecommunication studies.

	Scenario	Mean	Median	SD	Min	Max
Frequency (per min.)	**Co-located**	2.78	2.60	1.01	1.00	4.54
	Distributed	1.64	1.43	0.94	0.0	3.55
Start (%)	**Co-located**	11.04	3.55	13.55	0.37	42.68
	Distributed	28.16	22.55	26.74	0.50	100.00
Interval (%)	**Co-located**	83.77	87.22	12.44	55.23	97.67
	Distributed	58.00	61.32	30.11	0.00	99.17
Help Initiate (per min.)	**Co-located**	0.75	0.76	0.36	0.25	1.35
	Distributed	0.78	0.71	0.46	0.00	1.46
Help Response (per min.)	**Co-located**	0.73	0.76	0.39	0.00	1.35
	Distributed	0.64	0.57	0.42	0.00	1.30
Response Time (sec)	**Co-located**	1.42	1.30	0.53	1.00	2.70
	Distributed	2.23	2.30	0.98	0.00	3.80

Table 5.21 – Basic descriptive results for *Players Communication*

Help Initiate: Number of communication attempts for help (ask and offer) *per minute* during communication interval.

Help Response: Number of responses received for help initiation (affirmative and negative) *per minute* during communication interval.

Response Time: Average response time (in seconds) between the participants when they communicate for help.

To find out these *Communication* sub-factors and their effect on the COLLABORATION work for each group, this research used the data extracted from system logs and video recordings of experiment sessions as explained previously in Chapter 3.

5.3.2.1 Basic descriptive findings

In this subsection, the basic descriptive statistical findings are presented in Table 5.21 for the six aforementioned sub-factors of *Communication*: *Frequency*, *Start*, *Interval*, *Help Initiate*, *Help Response*, and *Response Time* in the two conditions.

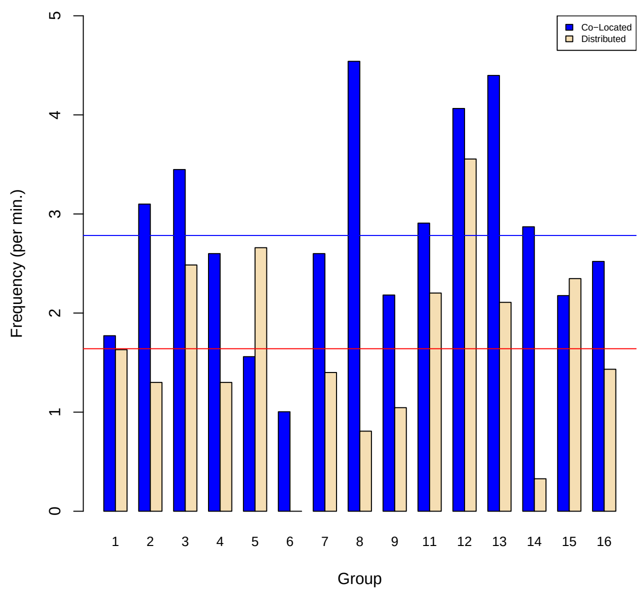


Figure 5.17 – *Communication Frequency* differences between the two conditions

5.3.2.2 Investigating differences

Frequency

Hypothesis C.5: *There is no difference between the means of communication frequency per minute in the two conditions.*

A paired-samples t-test was conducted to compare the *Communication Frequency* per minute in the co-located and distributed conditions. There was a **significant** difference in the scores of *Communication Frequency* per minute for the co-located and distributed conditions; $t(14) = 3.81$, $p \leq 0.05$, (95% confidence interval: 0.5, 1.8). Figure 5.17 illustrates the *communication frequency* differences between the two conditions for all the groups.

Hypothesis **C.5** test: **Reject**.

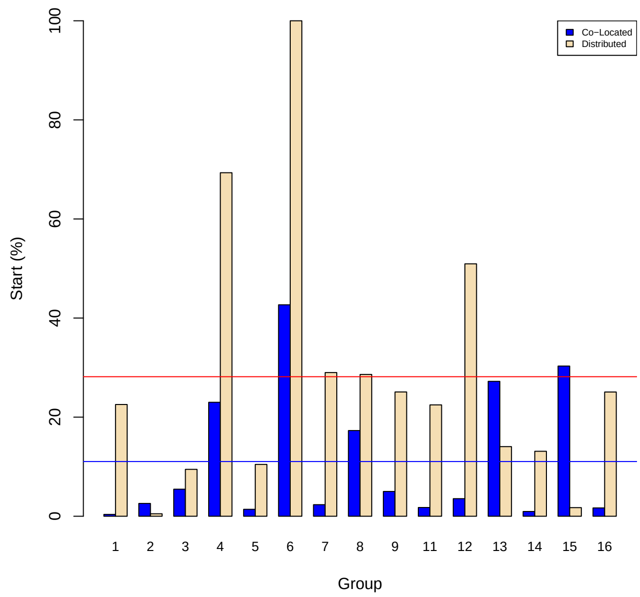


Figure 5.18 – *Communication Start Time* differences between the two conditions

Start

> ***Hypothesis C.6***: *There is no difference between the means of communication start time in the two conditions.*
>
> A paired-samples t-test was conducted to compare the *Communication Start Time* in the co-located and distributed conditions. There was a **significant** difference in the scores of *Communication Start Time* for the co-located and distributed conditions; $t(14) = -2.9$, $p \leq 0.05$, (95% confidence interval: -29.7, -4.53). Figure 5.18 illustrates the *communication start time* differences between the two conditions for all the groups.
>
> Hypothesis **C.6** test: **Reject**.

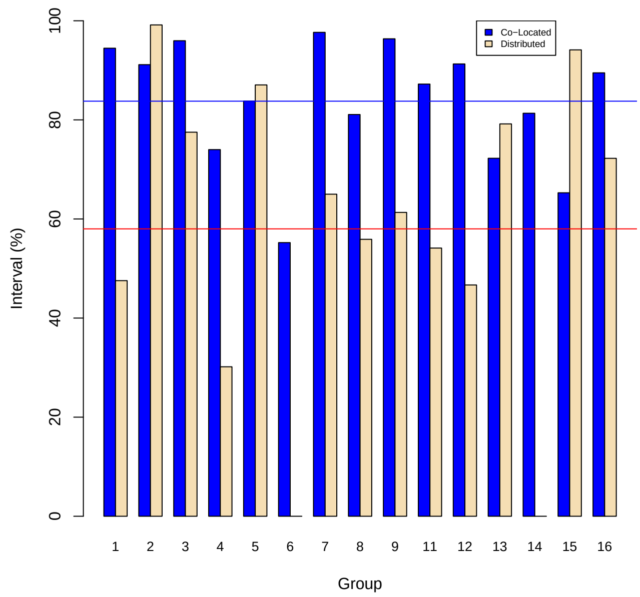


Figure 5.19 – *Communication Interval* differences between the two conditions

Interval

Hypothesis C.7: *There is no difference between the means of communication interval in the two conditions.*

A paired-samples t-test was conducted to compare the *Communication Interval* in the co-located and distributed conditions. There was **significant** difference in the scores of *Communication Interval* for the co-located and distributed conditions; $t(14) = 3.5$, $p \leq 0.05$, (95% confidence interval: 9.94, 41.60). Figure 5.19 illustrates the *communication interval* differences between the two conditions for all the groups.

Hypothesis **C.7** test: **Reject**.

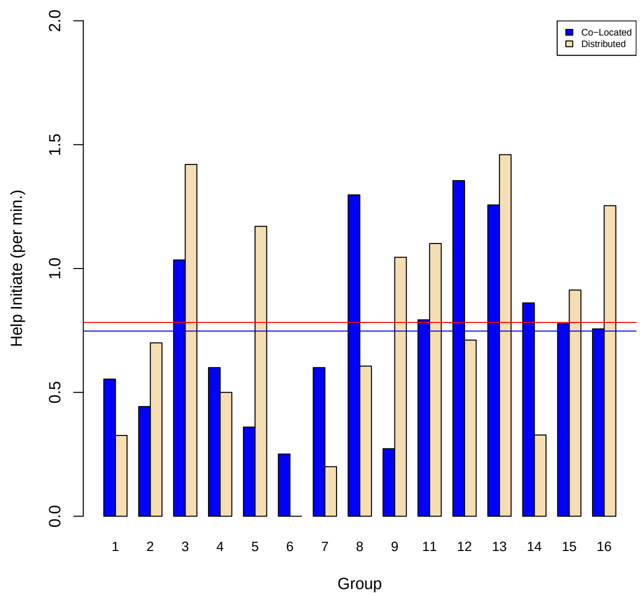


Figure 5.20 – *Communication Help Initiate* differences between the two conditions

Help Initiate

Hypothesis C.8: *There is no difference between the means of help initiation times per minute in the two conditions.*

A paired-samples t-test was conducted to compare the number of times a member *asked for/offered help* per minute in the co-located and distributed conditions. There was no significant difference in the scores of number of times a member *asked for/offered help* per minute for the co-located and distributed conditions; $t(14) = -0.3$, $p > 0.05$, (95% confidence interval: -0.30, 0.23). Figure 5.20 illustrates the *help initiation* differences between the two conditions for all the groups.

Hypothesis **C.8** test: **Fail to Reject**.

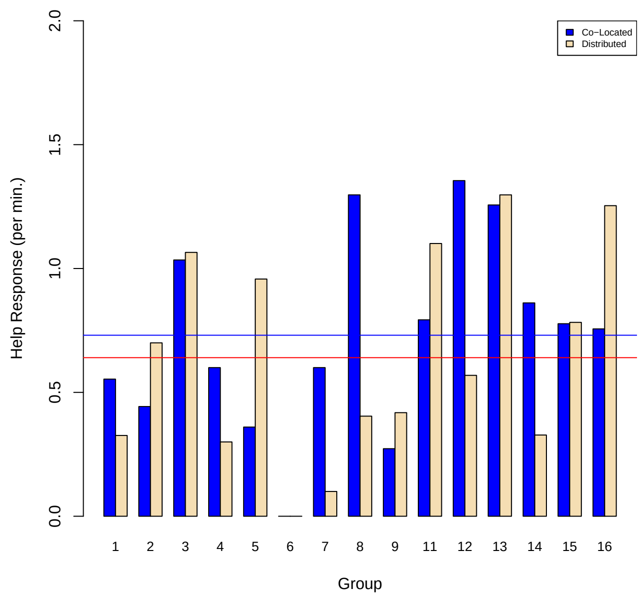


Figure 5.21 – *Communication Help Response* differences between the two conditions

Help Response

Hypothesis C.9: *There is no difference between the means of help response times per minute in the two conditions.*

A paired-samples t-test was conducted to compare the number of times a member *responded to help* per minute in the co-located and distributed conditions. There was no significant difference in the scores of number of times a member *responded to help* per minute for the co-located and distributed conditions; $t(14) = 0.79$, $p > 0.05$, (95% confidence interval: -0.16, 0.34). Figure 5.21 illustrates the *help response* differences between the two conditions for all the groups.

Hypothesis **C.9** test: **Fail to Reject**.

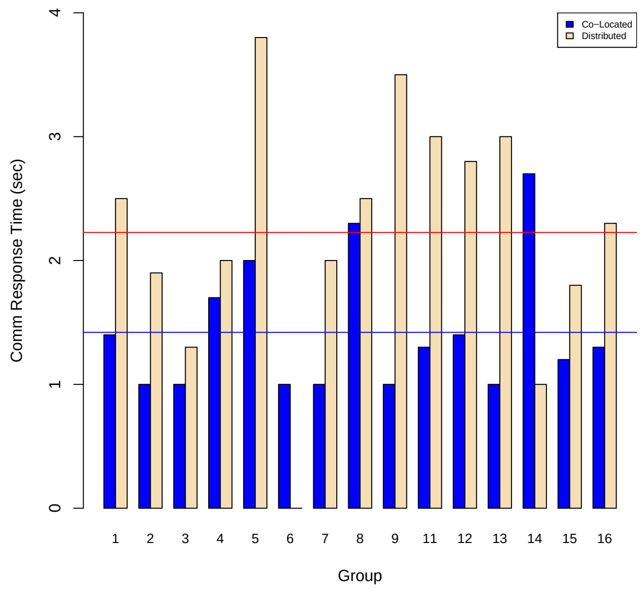


Figure 5.22 – *Communication Response Time* differences between the two conditions

Response Time

Hypothesis C.10: *There is no difference between the means of response time in the two conditions.*

A paired-samples t-test was conducted to compare the means of *response time* in the co-located and distributed conditions. There was a **significant** difference in the scores of *response time* for the co-located and distributed conditions; $t(14) = -2.83$, $p \leq 0.05$, (95% confidence interval: -1.42, -0.2). Figure 5.22 illustrates the *response time* differences between the two conditions for all the groups.

Hypothesis **C.10** test: **Reject**.

5.3.3 Contribution balance

Studying *Contribution Balance* has an important role in COLLABORATION analysis as it shows the equity of participation towards the given task by the participants. In

		Scenario	Mean	Median	SD	Min	Max
Work	***Participant 1***	**Co-located**	14.5	14.5	3.7	7.5	23.0
		Distributed	17.7	17.7	4.0	11.1	25.9
	Participant 2	**Co-located**	14.7	15.4	4.7	7.7	22.1
		Distributed	17.1	16.7	4.4	10.8	25.0
Communication	***Participant 1***	**Co-located**	0.4	0.3	0.3	0.0	1.3
		Distributed	0.5	0.3	0.4	0.0	1.4
	Participant 2	**Co-located**	0.4	0.3	0.3	0.0	1.0
		Distributed	0.3	0.3	0.3	0.0	1.1

Table 5.22 – Basic descriptive results for *Contribution Balance*

this research, the equity of participation is analysed for both experimental conditions, co-located and distributed. A Gini Coefficient technique is used for this part of the study; it has been used previously in collaboration research to analyse contribution balance [14, 56]. The aspects of contribution that are taken into consideration are:

Work: Total number of solved questions (correct and incorrect) per minute.
Communication: Total number of communication attempts per minute.

To find out these *Contribution Balance* sub-factors and their effect on the COLLABORATION work for each group, this research used the data extracted from system logs and video recordings of experiment sessions as explained previously in Subsection 3.3.2.2 and Subsection 3.3.2.3.

5.3.3.1 Basic descriptive findings

In this subsection, the basic descriptive statistical findings are presented in Table 5.22 for the two aforementioned sub-factors of *Contribution Balance*: *Work* and *Communication* in the two conditions. Table 5.23 shows the Gini Coefficient for all the groups as well.

	Scenario	Mean	Median	SD	Min	Max
Work	**Co-located**	0.21	0.20	0.03	0.19	0.30
	Distributed	0.25	0.25	0.02	0.24	0.29
Communication	**Co-located**	0.43	0.43	0.17	0.19	0.59
	Distributed	0.39	0.34	0.19	0.0	0.62

Table 5.23 – Gini Coefficient for all the groups

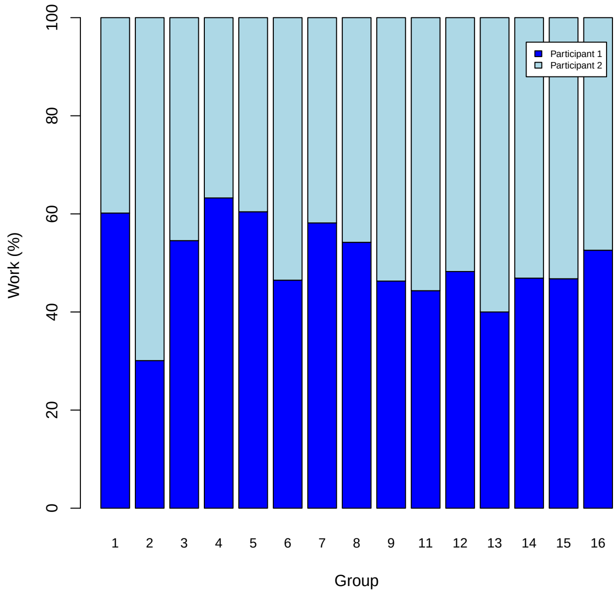
5.3.3.2 Investigating differences

Work

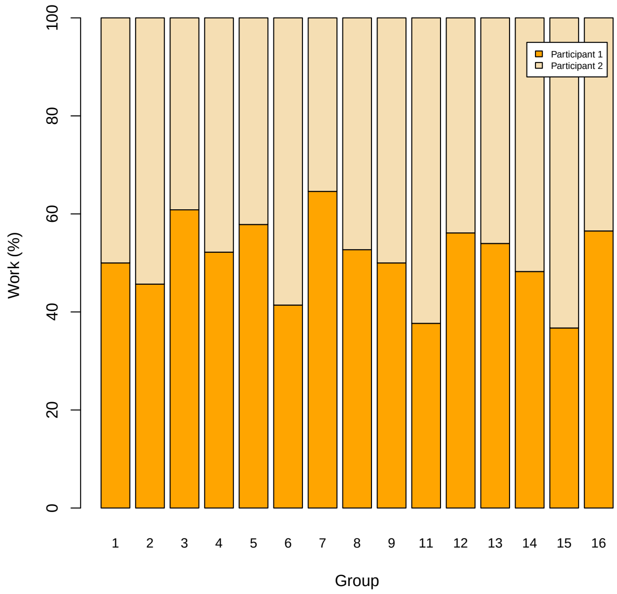
Hypothesis C.11: *There is no difference between the means of Gini Index for work contribution in the two conditions.*

A paired-samples t-test was conducted to compare the *Gini Index for Work contribution* in the co-located and distributed conditions. There was a **significant** difference in the scores of *Gini Index for Work contribution* for the co-located and distributed conditions; $t(14) = -4.28$, $p \leq 0.05$, (95% confidence interval: -0.06, -0.02). Figures 5.23 and 5.24 illustrates the *Gini index for work* differences between the two conditions for all the groups.

Hypothesis **C.11** test: **Reject**.



(a) Co-located



(b) Distributed

Figure 5.23 – *Work contribution* differences between the two conditions

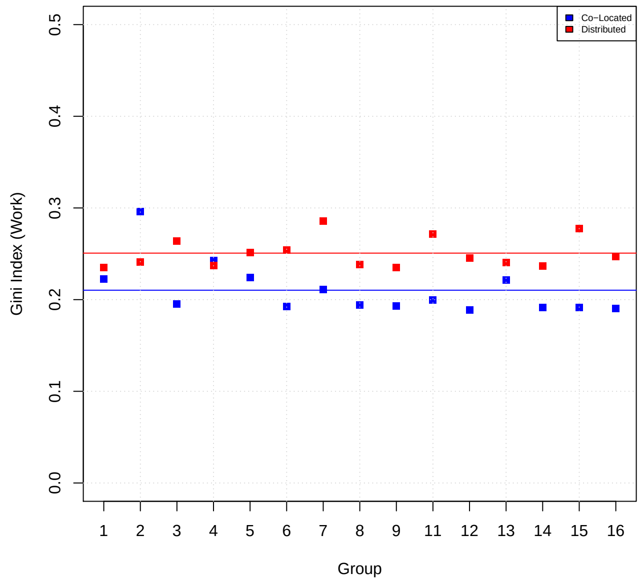


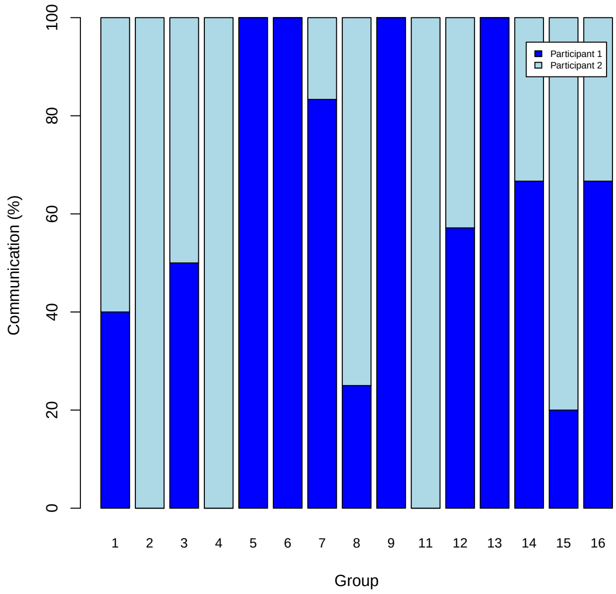
Figure 5.24 – *Gini Index for Work contribution* differences between the two conditions

Communication

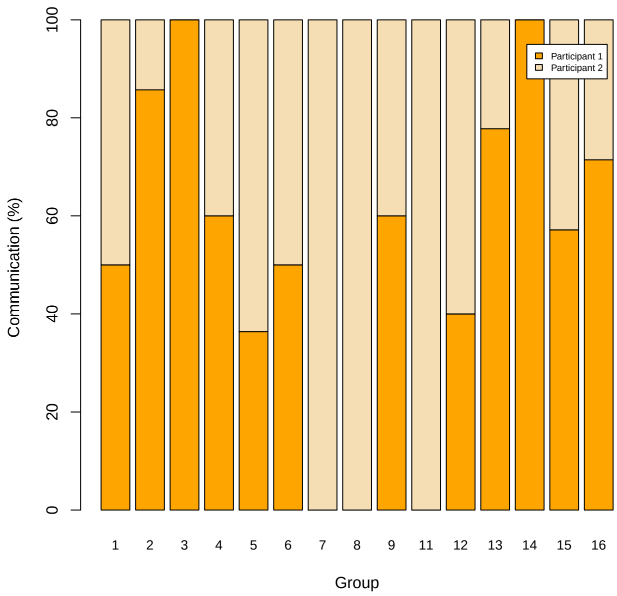
Hypothesis C.12: *There is no difference between the means of Gini Index for communication contribution in the two conditions.*

A paired-samples t-test was conducted to compare the *Gini Index for Communication contribution* in the co-located and distributed conditions. There was no significant difference in the scores of *Gini Index for Communication contribution* for the co-located and distributed conditions; $t(14) = 0.57$, $p > 0.05$, (95% confidence interval: -0.12, 0.20). Figures 5.25 and 5.26 illustrates the *Gini index for communication* differences between the two conditions for all the groups.

Hypothesis **C.12** test: **Fail to Reject**.



(a) Co-located



(b) Distributed

Figure 5.25 – *Communication contribution* differences between the two conditions

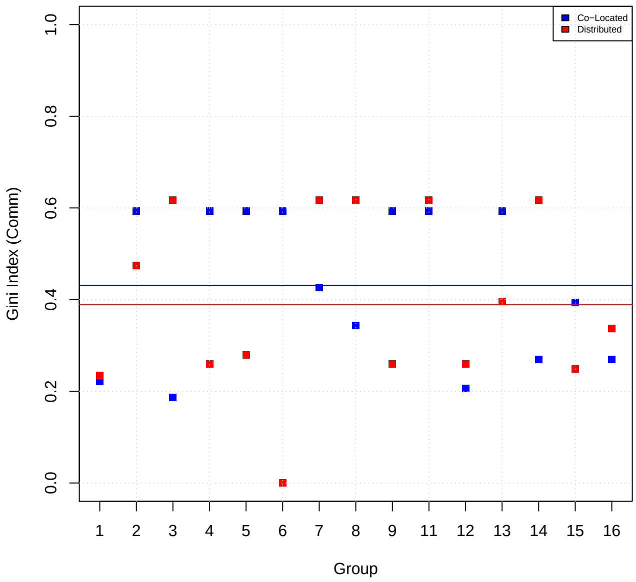


Figure 5.26 – *Gini Index for Communication contribution* differences between the two conditions

5.3.4 Summary

In this section (Group Members Collaboration), the results related to COLLABORATION has been presented and analysed. The area of COLLABORATION is divided into three sub-areas: *Styles*, *Communication*, and *Balance*. For each sub-area, the study findings has been compared to find out whether there are significant differences between the two conditions, co-located and distributed. A detailed discussion of these results is in Section 6.3.

5.4 System Usability

System USABILITY is studied and analysed as a result of the experimental work of this study. As shown previously in Chapter 2, usability is a very important aspect to take into consideration when designing systems that have high level of user engagement and interaction such as games [24]. Multi-touch and games usability factors have been analysed in separate studies such as [125] and [69]. Some other studies focused on the usability of distributed groupware in general [52]. In this research, usability is analysed to take all areas into consideration together.

This section focuses on three major areas of USABILITY: *Satisfaction*, *Ease of use and learn*, and *Physical and cognition demand*. These areas are considered the common base for usability studies [50, 78]. *Satisfaction* analyses the user subjective satisfaction with the interaction experience (see Subsection 5.4.2.1). *Ease of use and learn* is the analysis of how easily the user can learn to interact with the new system and to complete the given task (see Subsection 5.4.2.2). And *Physical and cognition demand* analyses the level of physical or cognitive requirements that the system exerts on users (see Subsection 5.4.2.3). The related results of these areas shall be presented in this section; with investigation of differences in both conditions, co-located and distributed.

Questionnaires filled by participants are used as the data source for this part of the analysis. Each participant filled two questionnaires in the experiment session, one for each condition (see Appendices A and B). The questions are then grouped into three different categories for the three USABILITY areas mentioned above. As a common practice when using Likert scale[4] questionnaires [78], scores of the grouped questions are summed up to give a total score for each area as shown in Table 5.24. General questions are added to both conditions, while questions that are specific to conditions are printed in **bold** face. Differences between the two experimental conditions, co-located and distributed, are investigated using the *t-test* statistical method (see Subsection 3.2.3) to calculate the significance of the difference in means. The reliability of the results is considered in a 95% confidence interval.

[4] Likert scale is explained in Subsection 3.3.2.1.

	Co-located	Distributed
Usability Area	**Questions**	**Questions**
Satisfaction	3, 9, 10, 11, 12, 13, 14, **17, 23, 27**	3, 9, 10, 11, 12, 13, 14, **30, 36, 40**
Ease of use and learn	5, 6, 7, 8, 11, 13, 14, 15, 16, **18, 19, 21, 22, 24, 25, 26, 28, 29**	5, 6, 7, 8, 11, 13, 14, 15, 16, **31, 32, 34, 35, 37, 38, 39, 41, 42**
Physical and cognition demand	1, 2, 4, 8, **20, 21, 27, 29**	1, 2, 4, 8, **33, 34, 40, 42**

Table 5.24 – USABILITY three areas questions grouping

5.4.1 Basic descriptive findings

In this subsection, the basic descriptive statistical results are presented in two parts, general findings (in Subsection 5.4.1.2) for the experiment in general, and comparative findings (in Subsection 5.4.1.3) where results in co-located and distributed scenarios are compared. Tables 5.25 and 5.26 present a briefing of the basic results extracted from the questionnaires when usability data is analysed. More detailed results for each question can be found in Appendix A.

5.4.1.1 Central tendency interpretation

Central tendency is a measurement of where the average responses to a question is mostly accumulated. All questions in the questionnaires were designed to have only one of four answers: *Strongly Agree, Agree, Disagree, and Strongly Disagree.* These answers are numbered *1, 2, 3*, and *4* respectively. The most common statistical measures used for Likert scales are mode, median, and interquartile range (IQR)[5].

5.4.1.2 General findings

These questions were used to gauge general usability aspects that are not specific to either scenario. The results of these questions are briefed in Table 5.25.

[5] Mean and standard deviation measures are not used as they assume continuous interval data while Likert scales are considered discrete ordinal data[67].

	Question	Mode	Median	IQR
Q.1	I have played group/network computer games before	2	2.5	1
Q.2	In general, I like games that require mathematics skills	1	1.5	1
Q.3	I like working in a team	1	1	1
Q.4	I am familiar with using multi-touch devices	1	2	2
Q.5	I quickly understood how to interact with the interface	1	1	1
Q.6	The displayed information was easy to read	1	1	1
Q.7	The organisation of information on the display surface was clear	1	1	1
Q.8	Connecting links to panels by dragging lines was easy to do	2	2	0.75
Q.9	Overall, I am satisfied with how easy it is to use the multi-touch interface	1	1	1
Q.10	I enjoy working with a remote team-mate more than a nearby one	3	3	1
Q.11	The physical absence of my team-mate affected my performance negatively	2	2	1
Q.12	I did not like being asked for help from my team-mate	3	3	1
Q.13	I would like to have text chatting feature with my team-mate	3	3	1
Q.14	I would like to have voice communication feature with my team-mate	2	2	1
Q.15	In general, it was easier to work alone on the table without somebody else next to me	3	3	1
Q.16	I found the messaging buttons more efficient in communicating with my team-mate	2	3	1.75

Table 5.25 – Basic results for general questions

As mentioned before, these questions are grouped according to the three areas of USABILITY. The grouping is done as the following:

Satisfaction: Questions 3, 9, 10, 11, 12, 13, and 14
Ease of use and learn: Questions 5, 6, 7, 8, 11, 13, 14, 15, and 16
Physical and cognition demand: Questions 1, 2, 4, and 8

		Co-located			Distributed		
	Question	Mode	Median	IQR	Mode	Median	IQR
Q.17/30	I enjoyed the game experience	1	1	1	1	1	1.75
Q.18/31	It was easy to learn how to play the game	1	1	1	2	2	1
Q.19/32	The information provided prior the game was clear and easy to understand	1	1	0	1	1	1
Q.20/33	I participated in solving the given mathematical problems	1	1	1	1	1	1
Q.21/34	The timing of the problems was challenging	2	2	1	2	2	1
Q.22/35	I found it easy to get involved in the activity	1	1	1	2	1.5	1
Q.23/36	The game encourages working together like a team	1	1	0	2	1	1
Q.24/37	I frequently offered help to my team-mate	2	2	1	2	2	1
Q.25/38	I frequently asked for help from my team-mate	2	2	1	2	2	1
Q.26/39	I found the game easy to play without helping each other as a team	3	3	1	3	3	1
Q.27/40	I was aware of my team-mate work and progress	2	2	1	3	2	1
Q.28/41	I frequently moved and rotated my panel in order to suit the location of work	2	2	1	2	2	1
Q.29/42	It was easy to interact with the game from any position around the table	2	2	1	2	2	1

Table 5.26 – Basic results for comparative questions

5.4.1.3 Comparative findings

Questions from 17 to 29 were about the user experience in the co-located scenario, while questions from 30 to 42 are the corresponding questions in the distributed scenario. These two groups of questions formed the basis for the USABILITY comparison analysis. The results of these questions are briefed in Table 5.26. In next subsection, the differences are formally investigated to find out how the three USABILITY aspects are affected by the experimental condition, col-located and distributed.

	Question	*t (29)*	*p*-value	Confidence Interval
Q.17/30	I enjoyed the game experience	9.89	≤ 0.05	(1.43, 2.17)
Q.18/31	It was easy to learn how to play the game	3.17	≤ 0.05	(0.25, 1.15)
Q.19/32	The information provided prior the game was clear and easy to understand	11.79	≤ 0.05	(1.29, 1.84)
Q.20/33	I participated in solving the given mathematical problems	0.14	> 0.05	(-0.44, 0.51)
Q.21/34	The timing of the problems was challenging	2.05	≤ 0.05	(0, 0.8)
Q.22/35	I found it easy to get involved in the activity	1.73	> 0.05	(-0.06, 0.66)
Q.23/36	The game encourages working together like a team	5.09	≤ 0.05	(0.66, 1.54)
Q.24/37	I frequently offered help to my team-mate	-1.24	> 0.05	(-0.53, 0.13)
Q.25/38	I frequently asked for help from my team-mate	-0.62	> 0.05	(-0.43, 0.23)
Q.26/39	I found the game easy to play without helping each other as a team	-1.14	> 0.05	(-0.28, 0.08)
Q.27/40	I was aware of my team-mate work and progress	0.33	> 0.05	(-0.17, 0.24)
Q.28/41	I frequently moved and rotated my panel in order to suit the location of work	-0.25	> 0.05	(-0.3, 0.23)
Q.29/42	It was easy to interact with the game from any position around the table	-2.69	≤ 0.05	(-0.35, -0.05)

Table 5.27 – Detailed *t-test* results for comparative questions

5.4.2 Investigating differences

t-test is used to test whether there is a significance difference between the result for each question in the two conditions as described by Lazar et al. [78]. At first, Table 5.27 presents the results for each single question separately. The *p-value* result is printed in red colour when the difference is significant. After that, subsections 5.4.2.1, 5.4.2.2, and 5.4.2.3 present the test results when the questions are grouped in their corresponding USABILITY area, *Satisfaction*, *Ease of use and learn*, and *Physical and cognition demand*, respectively.

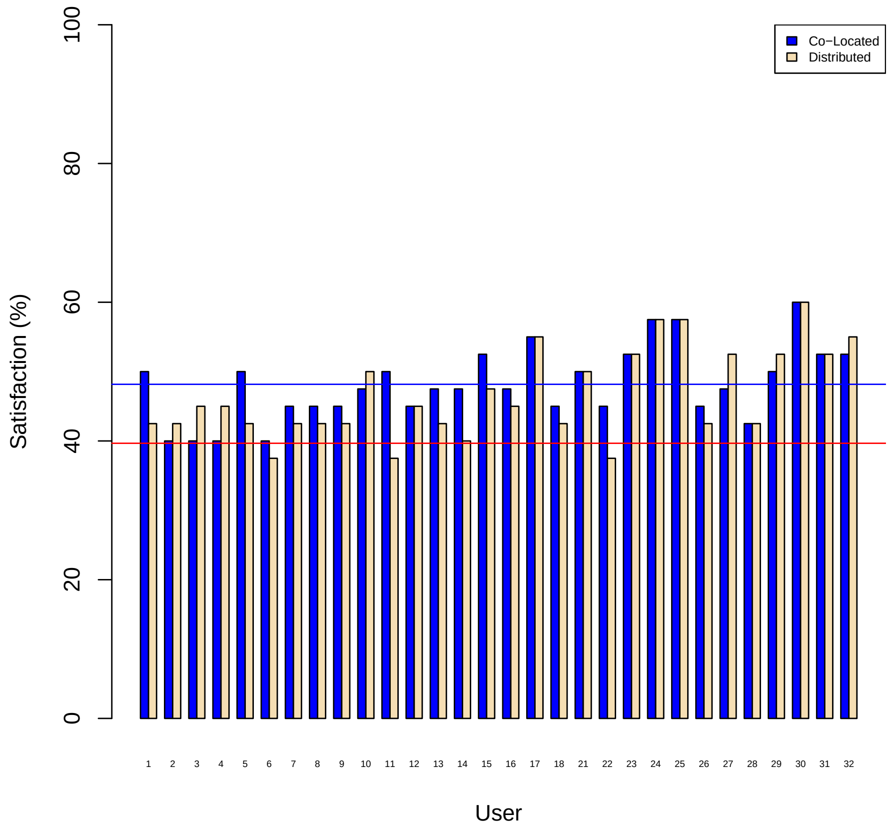


Figure 5.27 – *Total User Satisfaction* differences between the two conditions

5.4.2.1 Satisfaction

Hypothesis U.1: *There is no difference between the means of total user satisfaction in the two conditions.*

A paired-samples t-test was conducted to compare the *total user satisfaction* in the co-located and distributed conditions. There was a **significant** difference in the scores of *total user satisfaction* for the co-located and distributed conditions; $t(29) = -1.96$, $p \leq 0.05$, (95% confidence interval: -1.22, 0.02). Figure 5.27 illustrates the *user satisfaction* differences between the two conditions for all the users.

Hypothesis **U.1** test: **Reject**.

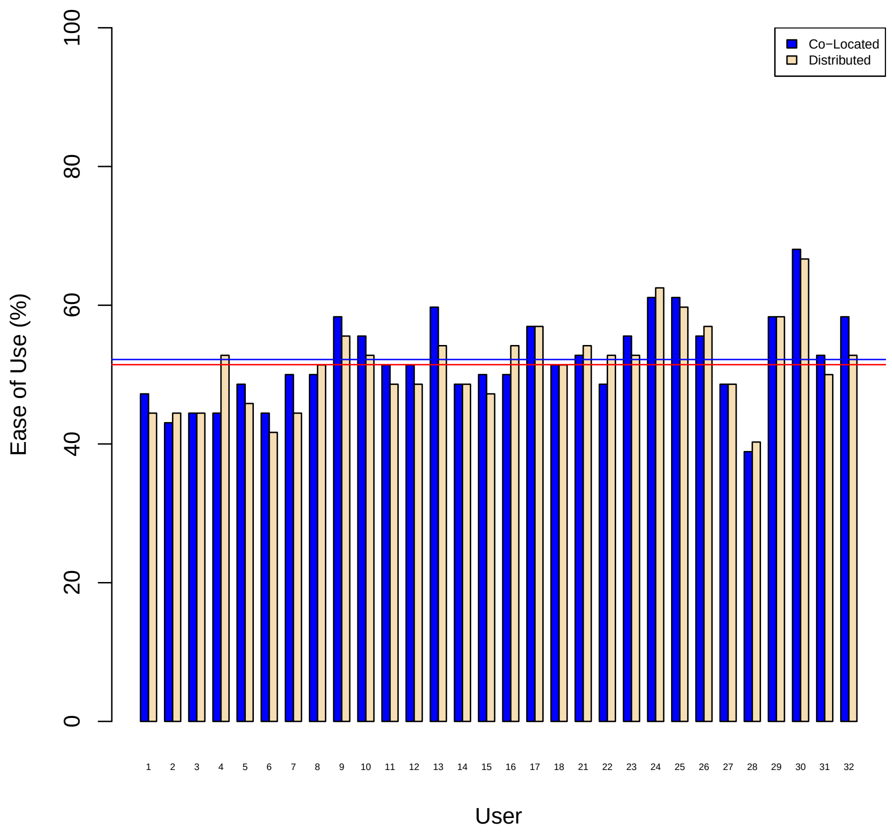


Figure 5.28 – *Total System Ease of Use and Learn* differences between the two conditions

5.4.2.2 Ease of use and learn

Hypothesis U.2: *There is no difference between the means of total system ease of use and learn in the two conditions.*

A paired-samples t-test was conducted to compare the *total system ease of use and learn* in the co-located and distributed conditions. There was no significant difference in the scores of *total system ease of use and learn* for the co-located and distributed conditions; $t(29) = -1.32$, $p > 0.05$, (95% confidence interval: -1.36, 0.29). Figure 5.28 illustrates the *ease of use and learn* differences between the two conditions for all the users.

Hypothesis **U.2** test: **Fail to Reject**.

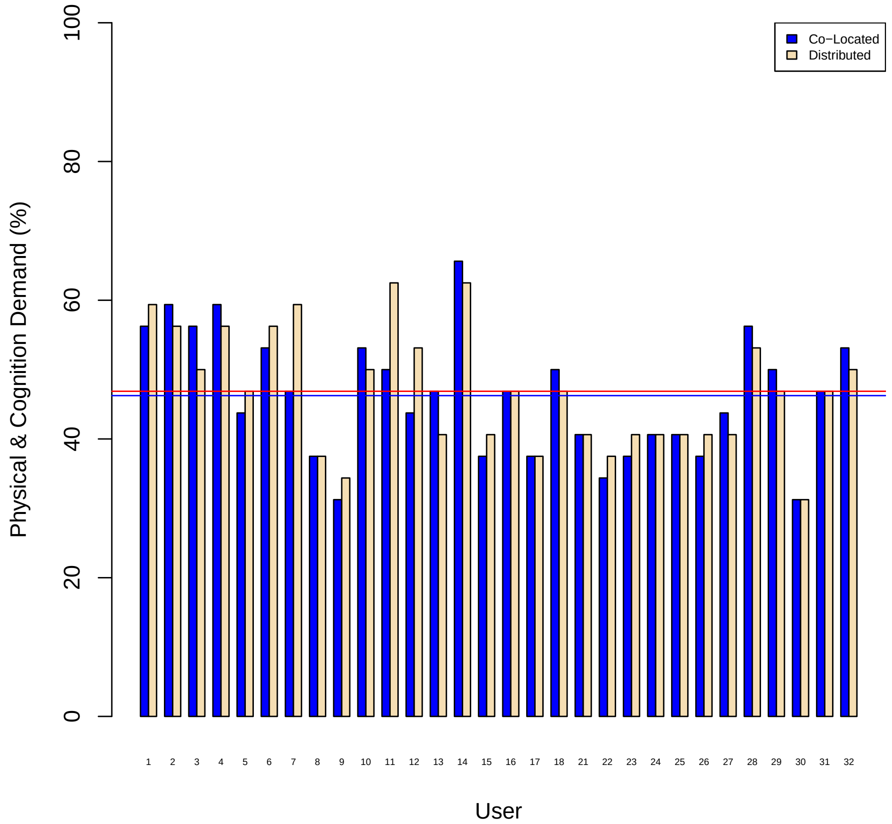


Figure 5.29 – *Total Physical and Cognition Demand* differences between the two conditions

5.4.2.3 Physical and cognition demand

Hypothesis U.3: *There is no difference between the means of total physical and cognition demand in the two conditions.*

A paired-samples t-test was conducted to compare the *total physical and cognition demand* in the co-located and distributed conditions. There was no significant difference in the scores of *total physical and cognition demand* for the co-located and distributed conditions; $t(29) = -0.73$, $p > 0.05$, (95% confidence interval: -0.76, 0.36). Figure 5.29 illustrates the *physical and cognition demand* differences between the two conditions for all the users.

Hypothesis **U.3** test: **Fail to Reject**.

	Satisfaction	***Ease of Use***	***Phys. Demand***
Satisfaction	1.0	0.77	0.48
Ease of Use	0.77	1.0	-0.58
Phys. Demand	0.48	0.58	1.0

Table 5.28 – USABILITY sub-factors r-coefficients in co-located scenario

5.4.3 Sub-factors correlations

In this subsection, the internal relationships among USABILITY sub-factors are investigated to get a deeper understanding effect size among each other. A correlation test between them is conducted to see how they interact and affect each other. Results from the correlation test reveal the following:

5.4.3.1 Co-located

There is a **strong** correlation between *Satisfaction* (mean= 20.7, sd= 2.1) and *Ease of use and learn* (mean= 34.4, sd= 4.6) in the co-located scenario. $r = 0.77$, $p \leq 0.05$, $n = 30$, $R^2 = 0.59$, (95% confidence interval: 0.56, 0.88).

There is a moderate correlation between *Satisfaction* (mean= 20.7, sd= 2.1) and *Physical and cognitive demand* (mean= 14.8, sd= 2.8) in the co-located scenario. $r = 0.48$, $p \leq 0.05$, $n = 30$, $R^2 = 0.23$, (95% confidence interval: 0.14, 0.72).

There is a **strong** negative correlation between *Physical and cognitive demand* (mean= 14.8, sd= 2.8) and *Ease of use and learn* (mean= 34.4, sd= 4.6) in the co-located scenario. $r = -0.58$, $p \leq 0.05$, $n = 30$, $R^2 = 0.34$, (95% confidence interval: 0.28, 0.78).

Table 5.28 and Figure 5.30 illustrate these relationships among USABILITY sub-factors. Table 5.29 is the *coefficient of determination (R^2)* matrix that shows the variability shared between the variables (see Subsection 3.2.4 for more details).

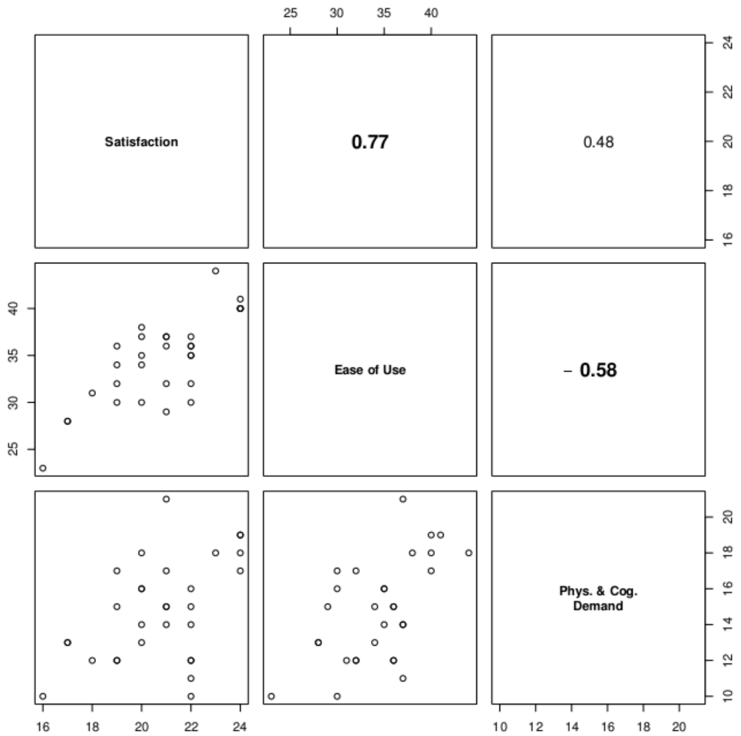


Figure 5.30 – USABILITY sub-factors correlation in co-located scenario

	Satisfaction	*Ease of Use*	*Phys. Demand*
Satisfaction	1.0	0.59	0.23
Ease of Use	0.59	1.0	0.34
Phys. Demand	0.23	0.34	1.0

Table 5.29 – USABILITY coefficient of determination in co-located scenario

5.4.3.2 Distributed

There is a **strong** correlation between *Satisfaction* (mean= 21.3, sd= 2.6) and *Ease of use and learn* (mean= 34.9, sd= 4.4) in the distributed scenario. $r = 0.65$, $p \leq 0.05$, $n = 30$, $R^2 = 0.42$, (95% confidence interval: 0.38, 0.82).

There is a moderate correlation between *Satisfaction* (mean= 21.3, sd= 2.6) and *Physical and cognitive demand* (mean= 15.0, sd= 2.75) in the distributed

	Satisfaction	***Ease of Use***	***Phys. Demand***
Satisfaction	1.0	0.65	0.49
Ease of Use	0.65	1.0	-0.67
Phys. Demand	0.49	0.67	1.0

Table 5.30 – USABILITY sub-factors r-coefficients in distributed scenario

	Satisfaction	***Ease of Use***	***Phys. Demand***
Satisfaction	1.0	0.42	0.24
Ease of Use	0.42	1.0	0.45
Phys. Demand	0.24	0.45	1.0

Table 5.31 – USABILITY coefficient of determination in distributed scenario

scenario. $r = 0.49$, $p \leq 0.05$, $n = 30$, $R^2 = 0.24$, (95% confidence interval: 0.16, 0.73).

There is a **strong** negative correlation between *Physical and cognitive demand* (mean= 15.0, sd= 2.75) and *Ease of use and learn* (mean= 34.9, sd= 4.4) in the distributed scenario. $r = -0.67$, $p \leq 0.05$, $n = 30$, $R^2 = 0.45$, (95% confidence interval: 0.40, 0.83).

Table 5.30 and Figure 5.31 illustrate these relationships among USABILITY sub-factors. Table 5.31 is the *coefficient of determination (R^2)* matrix that shows the variability shared between the variables (see Subsection 3.2.4 for more details).

5.4.3.3 Comparison

To put correlation findings in perspective, the r-coefficients in both scenarios are compared. Only the correlations that are statistically significant in co-located, distributed, or both are compared. Fisher's z-Transformation [26] test is applied on the correlation coefficients to find out the significance of difference between the coefficients in the two different scenarios. This is formulated in the following hypothesis.

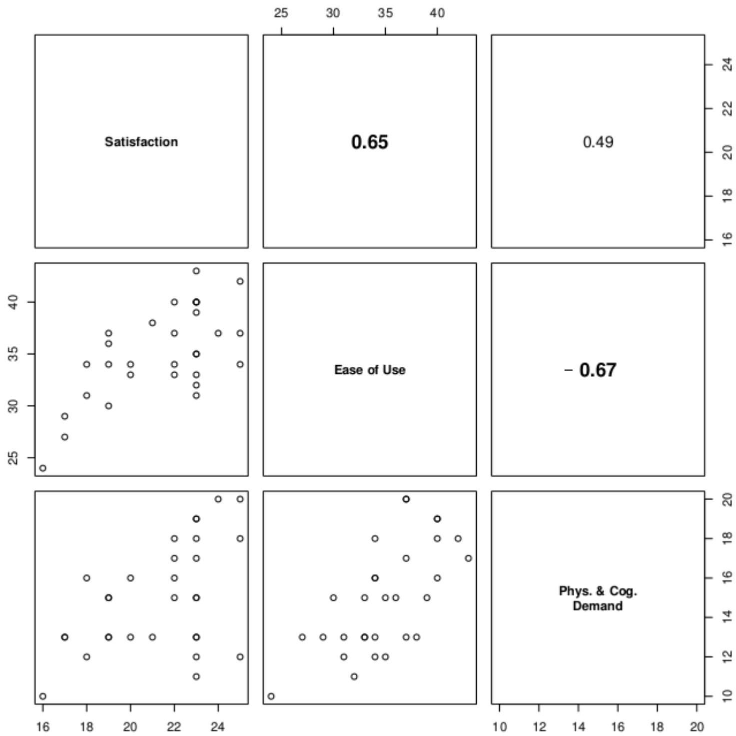


Figure 5.31 – USABILITY sub-factors correlation in distributed scenario

Hypothesis U.4: *There is no difference between the correlation coefficients among usability sub-factors in the two conditions.*

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Satisfaction* and *Ease of use and learn* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(30) = 0.9$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Satisfaction* and *Physical and cognitive demand* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(30) = 0.05$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Physical and cognitive demand* and *Ease of use and learn* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(30) = 0.54$, $p > 0.05$.

Hypothesis **U.4** test: **Fail to Reject**.

5.4.4 Summary

In this section (System Usability), the results related to USABILITY has been presented and analysed. The area of USABILITY is divided into three sub-areas: *Satisfaction*, *Ease of use and learn*, and *Physical and cognition demand*. The general usability findings is presented for each sub-area, then the findings has been compared to find out whether there are significant differences between the two conditions, co-located and distributed. A correlation test among the sub-areas has been carried out as well to investigate the internal relationships among the sub-factors. A detailed discussion of these results is in Section 6.4.

5.5 General Correlation Analysis

In this section, a correlation test is going to be carried out on the internal factors of PERFORMANCE, COLLABORATION, and USABILITY all together in the two study conditions, co-located and distributed. The purpose of this analysis is to find out whether the internal relationships among the underlying factors are affected between the two conditions. First, the correlation test results are presented for the co-located scenario, then for the distributed one. Finally, a comparison between the results is performed to check for any significant difference.

Notice that only new correlations between different areas sub-factors are presented here, i.e. the correlations that were already introduced are not considered in this section.

5.5.1 Correlation test results

Tables 5.32 and 5.33 show the strong correlation test results among the sub-factors in all areas for both scenarios. All other sub-factors combinations, which are not shown here, are considered either moderate or weak correlations[6]; and their test results were all insignificant. The columns of each table consist of the two tested sub-factors, the r-coefficient, the coefficient of determination (R^2), and the *p-value* which tells whether the correlation is significant ($p \leq 0.05$) or not.

[6] In addition to their minimal effect, there are tens of weak correlation results, which is impractical to present in this thesis.

Sub-factor 1	Sub-factor 2	*r*	*R²*	*p-value*
Speed	CH Collaboration Style	-0.52	0.27	≤ 0.05
Speed	VE Collaboration Style	-0.51	0.26	> 0.05
Incorrectness	Physical and Cognitive Demand	0.56	0.31	≤ 0.05
Added Difficulty	SSP Collaboration Style	-0.62	0.38	≤ 0.05
Satisfaction	Work Contribution Balance	0.69	0.48	≤ 0.05

Table 5.32 – Strong sub-factors correlations in co-located scenario

Sub-factor 1	Sub-factor 2	*r*	*R²*	*p-value*
Speed	SGP Collaboration Style	0.53	0.28	≤ 0.05
Help Initiation	Phys. & Cog. Demand	-0.57	0.32	≤ 0.05
Response Time	Phys. & Cog. Demand	-0.61	0.37	≤ 0.05

Table 5.33 – Strong sub-factors correlations in distributed scenario

5.5.2 Comparison

The r-coefficients that resulted in the previous correlation test in both scenarios are compared. Table 5.34 and Figure 5.32 illustrates the significant correlation relationships in co-located (blue) and distributed (red) scenarios. Only the correlations that were statistically significant are compared. Fisher's z-Transformation [26] test is applied on the correlation coefficients to find out the significance of difference between the coefficients in the two different scenarios. This is formulated in the following three hypotheses (*H.1*, *H.2*, and *H.3*).

Hypothesis H.1: *There is no difference between the correlation coefficients among the sub-factors of performance and collaboration in the two conditions.*

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Speed* and *CH Collaboration Style* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 0.97$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Speed* and *VE Collaboration Style* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 0.16$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Speed* and *SGP Collaboration Style* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 0.13$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Added Difficulty* and *SSP Collaboration Style* in the co-located and distributed conditions. There was a **significant** difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 2.30$, $p \leq 0.05$.

Hypothesis **H.1** test: **Reject (partially)**.

Hypothesis H.2: *There is no difference between the correlation coefficients among the sub-factors of performance and usability in the two conditions.*

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Incorrectness* and *Physical and cognitive demand* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 1.1$, $p > 0.05$.

Hypothesis **H.2** test: **Fail to Reject**.

Hypothesis H.3: *There is no difference between the correlation coefficients among the sub-factors of collaboration and usability in the two conditions.*

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Help Initiation* and *Physical and Cognitive Demand* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 0.55$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Response Time* and *Physical and Cognitive Demand* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 1.42$, $p > 0.05$.

Fisher's z-Transformation test was conducted to compare the correlation coefficients between *Satisfaction* and *Work Contribution Balance* in the co-located and distributed conditions. There was no significant difference in the coefficients scores for the co-located and distributed conditions; $z(15) = 0.89$, $p > 0.05$.

Hypothesis **H.3** test: **Fail to Reject**.

Sub-factor 1	Sub-factor 2	*r (COL)*	*r (DIS)*	*p-value*
Speed	CH Collaboration Style	-0.52	-0.48	> 0.05
Speed	VE Collaboration Style	-0.51	-0.46	> 0.05
Speed	SGP Collaboration Style	0.49	0.53	> 0.05
Added Difficulty	SSP Collaboration Style	-0.62	-0.14	≤ 0.05
Incorrectness	Phys. & Cog. Demand	0.56	0.18	> 0.05
Help Initiation	Phys. & Cog. Demand	-0.40	-0.57	> 0.05
Response Time	Phys. & Cog. Demand	-0.13	-0.61	> 0.05
Satisfaction	Work Cont. Balance	0.69	0.45	> 0.05

Table 5.34 – Significant sub-factors correlations coefficients in co-located and distributed scenarios

5.5.3 Summary

In this section (General Correlation Analysis), a correlation test among all the sub-factors of PERFORMANCE, COLLABORATION, AND USABILITY has been carried out for the two experimental conditions, co-located and distributed. The purpose of this test is to find whether the internal relationships among the sub-factors were affected by the location of participants. A detailed discussion of these results is in Section 6.5.

5.6 Chapter Summary

In this chapter (Data, Analysis, and Results), the data collected during the experimental sessions was presented and analysed. Data preparation and cleaning procedure were described; as well as an explanation of results interpretation. The sample's descriptive statistics were presented to give an idea about the participants who joined the experiment. After that, a detailed presentation and analysis of data and results was introduced for each major area of the research, PERFORMANCE, COLLABORATION, and USABILITY. For each area, the differences between the co-located and distributed scenarios were thoroughly investigated with correlation analysis if applicable. Finally, a general correlation test is done for all the sub-factors in the three areas to analyse the effect of relationship between the different aspects of the experiment.

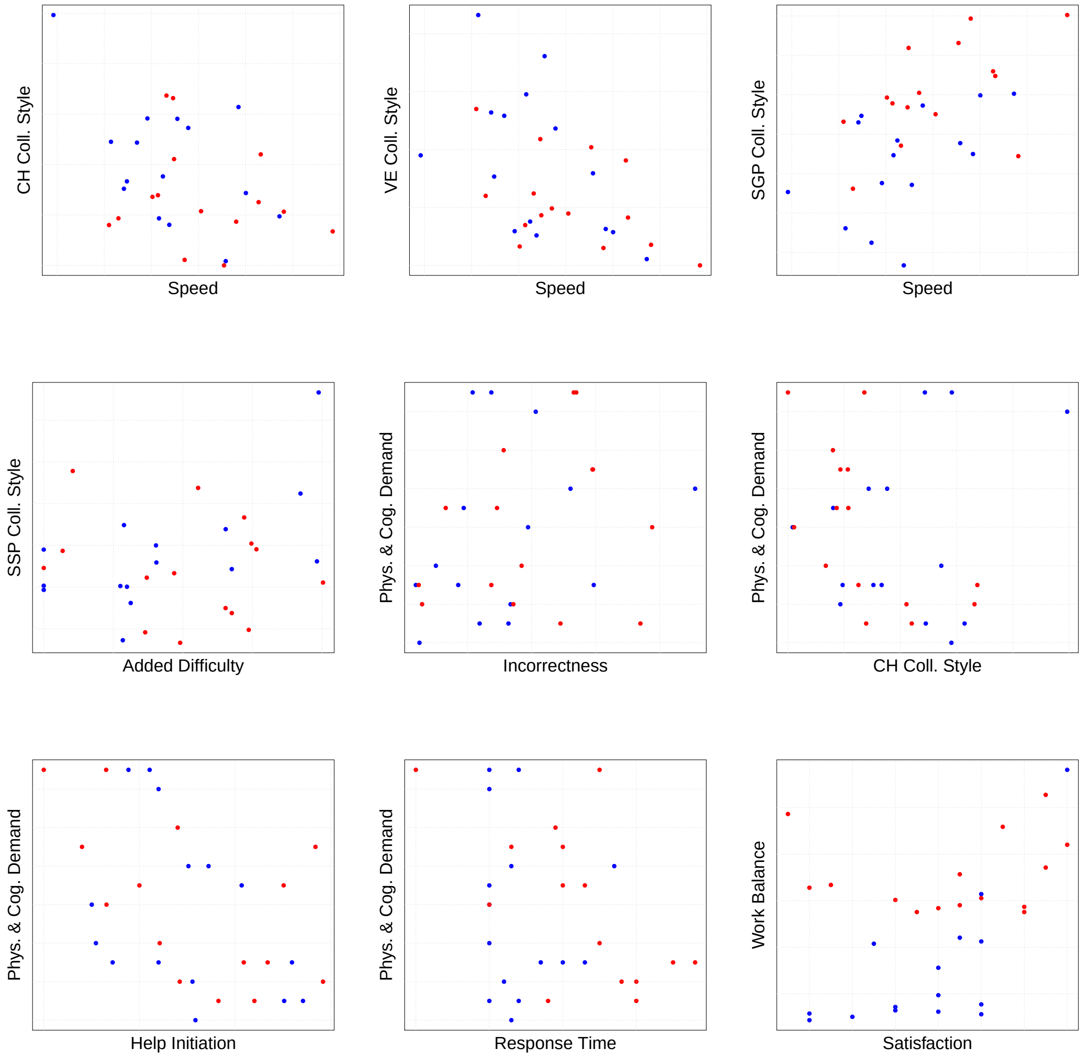


Figure 5.32 – Significant sub-factors correlations in co-located (blue) and distributed (red)

In the next chapter, all the results presented in this chapter are going to be discussed in details within the context of this research.

6 Discussion

This chapter will discuss the impact of physical position of participants (*col-located* and *distributed*) on the HCI aspects introduced throughout this research. The discussion is based on the findings presented in the previous chapter (Chapter 5) in order to draw conclusions related to the three areas of the research: PERFORMANCE, COLLABORATION, and USABILITY. The discussion structure shall be built around the proposed research questions in order to answer them within the context of the research and its background of previous work.

6.1 Hypotheses Test Briefing

Hypotheses are formulated to answer the research questions presented at the beginning of this research in Subsection 1.4.1. In investigating different areas and factors of this work, a hypothesis is presented on top of each piece of investigation, then the resulted data is analysed and tested against the hypothesis in order to reject it or not. As a quick reference, Tables 6.1, 6.2, 6.3, and 6.4 give a briefing of all the hypotheses used in this research and whether the statistical tests have resulted in "reject (✗)" or "fail to reject (✓)" them.

	Hypothesis	Test Result
P.1	There is no difference between the means of duration in the two conditions	✓
P.2	There is no difference between the means of effort in the two conditions	✗
P.3	There is no difference between the means of speed in the two conditions	✗
P.4	There is no difference between the means of incorrectness ratio in the two conditions	✓
P.5	There is no difference between the means of added difficulty ratio in the two conditions	✓
P.6	There is no difference between the means of unnecessary work ratio in the two conditions	✓
P.7	There is no difference between the correlation coefficients among performance sub-factors in the two conditions	✓

Table 6.1 – Performance hypotheses briefing

6.2 Performance

RQ 1: *Does group performance differ between the co-located and distributed scenarios?*[1]

In this section, the results found in PERFORMANCE analysis (Section 5.2) are discussed in order to understand the effects of distribution on the *Efficiency*, *Accuracy*, and internal correlations among the sub-factors. The research question is divided into three sub-questions according to the introduced aspects of PERFORMANCE.

6.2.1 Efficiency

RQ 1.1: *Does efficiency differ between the co-located and distributed scenarios?*

As shown in Subsection 5.2.1.2, the three sub-factors of *Efficiency* were investigated for differences between co-located and distributed scenarios. Results showed that although there is a difference in means of *duration* between co-located and distributed scenarios (in favour of the co-located), the difference is statistically insignificant. However, the differences are significant for the other two sub-factors, *effort* and *speed*.

[1] RQ: Research Question.

	Hypothesis	Test Result
C.1	There is no difference between the means of time spent in CH collaboration style in the two conditions	✓
C.2	There is no difference between the means of time spent in VE collaboration style in the two conditions	✗
C.3	There is no difference between the means of time spent in SGP collaboration style in the two conditions	✗
C.4	There is no difference between the means of time spent in SSP collaboration style in the two conditions	✓
C.5	There is no difference between the means of communication frequency per minute in the two conditions	✗
C.6	There is no difference between the means of communication start time in the two conditions	✗
C.7	There is no difference between the means of communication interval in the two conditions	✗
C.8	There is no difference between the means of help initiation times per minute in the two conditions	✓
C.9	There is no difference between the means of help response times per minute in the two conditions	✓
C.10	There is no difference between the means of response time in the two conditions	✗
C.11	There is no difference between the means of Gini Index for work contribution in the two conditions	✗
C.12	There is no difference between the means of Gini Index for communication contribution in the two conditions	✓

Table 6.2 – Collaboration hypotheses briefing

The difference in *effort* is for the advantage of co-located scenario, where the mean of *effort* is 32% less than that in distributed scenario. That gives an indication that more work has been done in the distributed scenario, which, supposedly, should significantly increase the *duration* based on the high correlation between *duration* and *effort* (Figure 5.5). However, the *duration* is not significantly affected by the increased *effort* in distributed scenario, and that can be explained by studying the third sub-factor, *speed*. Recall that *Speed* considers the number of questions correctly solved, i.e. those that cause progress.

	Hypothesis	Test Result
U.1	There is no difference between the means of total user satisfaction in the two conditions	✗
U.2	There is no difference between the means of total system ease of learn and use in the two conditions	✓
U.3	There is no difference between the means of total physical and cognition demand in the two conditions	✓
U.4	There is no difference between the correlation coefficients among usability sub-factors in the two conditions	✓

Table 6.3 – Usability hypotheses briefing

	Hypothesis	Test Result
H.1	There is no difference between the correlation coefficients among the sub-factors of performance and collaboration in the two conditions	✗ (*partially*)
H.2	There is no difference between the correlation coefficients among the sub-factors of performance and usability in the two conditions	✓
H.3	There is no difference between the correlation coefficients among the sub-factors of collaboration and usability in the two conditions	✓

Table 6.4 – Correlation hypothesis briefing

The difference in means for the *speed* sub-factor is in favour of the distributed condition; the mean of *speed* in distributed scenario is 11% higher than the mean in co-located scenario. This finding can counterbalance the effect of *effort* on *duration*, as more *speed* means less *duration*. The correlations of the *Efficiency* sub-factors are discussed in more details next.

When correlation coefficients are compared in both scenarios in Subsection 5.2.1.3, the results showed that there is no significant difference in *Efficiency* sub-factors correlations between the co-located and the distributed conditions. However, some interesting results could be drawn from this comparison. Figures 5.4 and 5.5 show that there is a strong relationship between *duration* and *effort*, and between *duration* and *speed* for each group, which is an expected result as the time needed to perform the task is supposed to increase when the number of questions is increased, and to decrease when the correctly answered questions are increased. In the distributed scenario, the relationship between *duration* and *effort* is slightly stronger, and the relationship between *duration* and *speed* is slightly weaker. That can be explained from the observation of the players: as they were closely working and plan their movements in the co-located condition, they spent more time on verbal conversation which resulted in less *effort* and a slower *speed*, but that conversation helped them to achieve the target in total in less time. However, as previously mentioned, the difference in *duration* is insignificant, hence the time that players gain in total in the co-located scenario is actually balanced by the fact that they are more efficient in the other sub-factors, the *effort* and *speed*.

6.2.2 Accuracy

RQ 1.2: *Does accuracy differ between the co-located and distributed scenarios?*

As shown in Subsection 5.2.2.2, the three sub-factors of *Accuracy* were investigated for differences between the co-located and the distributed scenarios. Results showed that the difference in the means of *incorrectness ratio* between the two conditions is statistically insignificant, despite it is, on average, in favour of the co-located scenario. Although answering questions correctly is an individual task, it is noticed that the number of correct answers is much higher in the co-located scenario. Numerically, the mean of *incorrectness ratio* is lower in the co-located scenario by 30% of that in the distributed one. This can be justified by recalling that *effort* is higher in the distributed scenario as shown in Figure 5.2, and *effort* is the total number of questions solved by a group including correct and incorrect answers.

The other two *Accuracy* sub-factors in concern are the *added difficulty ratio* and the *unnecessary work ratio*. Although the differences in means between the two scenarios for these sub-factors are for the advantage of the co-located condition, 15% and 20%, respectively, lower than those in distributed condition; the test showed that the differences are statistically insignificant (refer to Subsection 5.2.2.2).

Figures 5.9 and 5.10 show the correlations among the *Accuracy* underlying sub-factors. When a correlation test is carried out on these sub-factors, the results were insignificant in both scenarios as explained in Subsection 5.2.2.3; hence, no formal Fisher's z-Transformation test has been carried out.

6.2.3 Correlations

RQ 1.3: *Do correlations among performance sub-factors differ between the co-located and distributed scenarios?*

In this subsection, and based on the correlation findings in Subsection 5.2.3.1 and Subsection 5.2.3.2, PERFORMANCE sub-factors correlations are discussed for each scenario to understand the internal dynamics in the PERFORMANCE side of the research.

Although differences between correlations in both conditions were insignificant, it is noticed, in general, that the relationship between *Efficiency* and *Accuracy* follows what is common in human-computer interaction studies in which it is an inverse relationship; that is, *Efficiency* should decrease as *Accuracy* increases and vice versa [78, 32].

As mentioned before in Section 5.2, *Efficiency* is measured in this study by considering *duration*, *effort*, and *speed*, and *Accuracy* is measured by considering *incorrectness*, *added difficulty*, and *unnecessary work*. With reference to findings of the relevant sub-factors in Tables 5.14 and 5.17 for both scenarios, the correlations between *duration* in one side and *incorrectness*, *added difficulty*, and *unnecessary work* in the other side are -0.29, -0.34, and -0.12, respectively for the co-located scenario, and -0.35, -0.27, -0.09, respectively for the distributed scenario. These coefficients approve the assumption of Lazar [78] that *Efficiency* and *Accuracy* have an **inverse** relationship. The same conclusion can be drawn for the *effort* and *speed* sub-factors with two points to consider:

1. The relationship between *effort* and and *unnecessary work ratio* is 0 or a very weak positive correlation (0.09); this relationship result is intuitive as the more time a group spend in working on unnecessary parts of the games the more *effort* they put to finish that task
2. The r-coefficients between *speed* and other *Accuracy* sub-factors are positive. This is not contrary to the basic assumption of inverse relationship between *Efficiency* and *Accuracy*; *speed* affect *Efficiency* in a direct relationship, that is, the higher the *speed* the higher the *Efficiency*.

It is noticed that *Effort* correlation is weaker in co-located scenario than in distributed one. The reason for this weak effect is that the participants are more careful in answering the questions and selecting the links when they work on the same table, so the wrong answers and added difficulty are reduced compared to the distributed condition. It is also noticed that *speed* correlation is the strongest with *Accuracy* sub-factors. This is also an intuitive finding as explained by Dix [32]; the faster the participants are working the less focused on the questions and links they are, which will result in a higher inaccurate results rate, though the group efficiency is higher.

When these correlation coefficients were compared against each other for both scenarios in Subsection 5.2.3.3, the results showed that, statistically, there is no significant difference in group PERFORMANCE sub-factors relationships between the co-located and the distributed conditions.

6.2.4 Summary

Research question (**RQ 1**) was about whether there are differences in group PERFORMANCE factors between both scenarios (see Section 6.2). As the discussion has shown, the differences were only in the *Efficiency* factor, in particular, in the *effort* and *speed* sub-factors (**RQ 1.1**). The differences for the other factors were statistically insignificant (**RQ 1.2**), and hence, can be neglected. In addition, the differences in the correlation coefficients among those factors between both conditions were also statistically insignificant (**RQ 1.3**).

6.3 Collaboration

RQ 2: *Does participants collaboration differ between the co-located and distributed scenarios?*

In this section, the results found in COLLABORATION analysis (Section 5.3) are discussed in order to understand the effects of distribution on the *Styles*, *Communication*, and *Contribution Balance* among the sub-factors. The research question is divided into three sub-questions according to the introduced aspects of COLLABORATION.

6.3.1 Collaboration styles

RQ 2.1: *Do collaboration styles differ between the co-located and distributed scenarios?*

To investigate the differences between the two conditions in terms of collaboration style, four collaboration *styles* were adopted from Isenberg work [64], and analysed in this research. Those style are: communicating for help (*CH*), view engaged (*VE*), same specific problem (*SSP*), and same general problem (*SGP*). *CH*, *VE*, and *SSP styles* characterise the closely coupled participants, while *SGP* characterises the loosely coupled participants. This coupling categories are also suggested by Isenberg [64] who found that participants spend almost half of their time in closely coupled collaboration. Close collaboration is usually encouraged, hence systems should facilitate its styles as much as possible [13]. These particular styles were chosen because the participants performed them during the experiment as noticed by the researcher when analysing the video recordings[2]. Each collaboration style is calculated as a percentage of the total task time for each group in both conditions.

When collaboration *styles* were analysed in Subsection 5.3.1, it is found that participants spent 53.1% and 70.4% of their time in *SGP style* for co-located and distributed scenarios, respectively (see Table 5.20). That leaves, approximately, half of the time for other closely coupled styles in the co-located scenario, which conforms to what has been found by Isenberg [64]. However, the loosely coupled collaboration percentage is much higher in the distributed scenario, 70.4%, and that can give a strong indication of lack of work coordination and latency in asking for/offering help in the distributed condition.

The other style that has a significant difference is the *VE style,* 8.9% and 5.5%, for co-located and distributed scenarios, respectively. The nature of this style suggests this discrepancy as participants are more likely to get engage in observing each other's work in the co-located scenario [64]. *VE* is a closely coupled collaboration style, in which the participants engage in active communication in order to accomplish the required task [13]. In the co-located condition, the participants spend more time in close collaboration than in the distributed condition as shown in the ratios of *VE* style. The other two close collaboration styles are the *CH* and *SSP*; though the differences are statistically insignificant, but on average, the advantage went to the co-located scenario. This explains one aspect of why groups have better performance when the members set together on the same table.

To summarise, participants spent, in total, 45.3% and 36.4% of their time in close collaboration in the co-located and distributed scenarios, respectively. However, as

[2] Isenberg [64] mentioned other styles which are not relevant to this study, so they were excluded.

shown above, the differences in two of the close collaboration styles are statistically insignificant (*CH* and *SSP*), so the significant source of difference should be the *VE* style. This difference can be justified by the higher *SGP* style percentage in the distributed scenario. Participants spent significantly more time in the *SGP* collaboration style in the distributed scenario than in co-located scenario. Although, it is noticed that groups who developed an early assistance strategy in the distributed condition, to work more on the same parts of the problem together, have less *SGP* style and more *SSP* and *VE* styles, which gives a clear clue of high awareness and coordination.

6.3.2 Participants communication

RQ 2.2: *Does participants communication differ between the co-located and distributed scenarios?*

The type of communication that was analysed in this research was the assistance communication (see Subsection 5.3.2). In the distributed scenario, the participants were only able to ask for help or to offer help using a simplified messaging mechanism implemented in the game (see Chapter 4). In the co-located scenario, they were able to verbally communicate and talk to each other, however, only the conversation that was about assistance request or offer were considered to be able to compare both conditions on the same level. However, other conversation were also recorded, but they were very short and with no real effect on participants work.

Communication between participants was analysed with six parameters that reflects the common aspects of any communication activity. These aspects were introduced in Subsection 5.3.2. Discussing differences and similarities between the two conditions for these aspects will help in understanding the importance of communication for such types of applications in general [63, 140, 104], and the effectiveness of the messaging sub-system that the participants used in the distributed scenario.

It is noticed that the differences are on the time related aspects of communication (*frequency*, *start time*, *interval*, and *response time*), while the differences in the other aspects (*help initiation* and *help response*) are statistically insignificant. Participants have communicated 2.78 and 1.64 times per minute in the co-located and distributed scenarios, respectively. These numbers should not be taken by themselves without understanding the context of the task; higher frequency is not always an advantage especially in the co-located condition as it could be a real source of distraction. When participants work together on the same table, asking for help or offering help is much easier and rejecting the request is not easy because of psychological effects of being in front of each other [52]. As found by studying the questionnaires and videos of the participants, they usually could not reject an assistance request from their team-mates in the co-located scenario, while they found that easier in the distributed scenario. It is also found that the excessive communication for assistance in the co-located condition has actually distracted the participants especially when they are not equally skilled in solving the problem. In one extreme case, they could not solve the problem at all because one of them was very slow and required the other participant's help in every movement which resulted in a "game over" state.

In the *start time* parameter, it was very obvious that participants needed, on average, much more time in the distributed scenario to start to communicate with each other. They started communication after they went 11.04% of total time in co-located condition, while they waited until they went 28.16% of total time in distributed condition. That delay in starting communication has severely affected some of the groups performance in the distributed scenario. They did not appreciate the importance of helping each other until they lost a good amount of time, as they thought they could solve the problem individually. That gives an indication that a more rigid instructions should have been delivered to the participants before they start in the distributed condition, or it might, also, indicate that the participants are unused to working in collaborative environments.

The participants stayed in communication for an *interval* of 83.8% and 58.0% of the total time in the co-located and distributed conditions, receptively. The longer the collaborators stay in contact, the better the results they have [52]; that was obvious in the results although the correlation between *interval* and PERFORMANCE aspects was not strong. What actually affected the *interval* variable is the *start time*; as explained before, groups started to communicate vary late in the distributed scenario, and that made the total *interval* of communication shorter than the *interval* in co-located scenario. The end of communication was almost the same in both conditions, and some groups stayed in contact until the last moment.

Response time for an assistance request or offer was 1.42 and 2.23 seconds for co-located and distributed conditions, respectively. Webb [147] has discussed the importance of getting a response to help requests between team-mates; the shorter the response time the less frustrated the requester will be. It is clear that *response time* is shorter in co-located scenario by 36%. This is explained by the fact that direct physical communication is more natural and outperform simulated communication mechanisms as illustrated by Brave [22] and Dourish [33]; that makes requests clearer and responses faster. A sophisticated communication system could enhance the whole experience, which could be by implementing a more flexible text chat messaging mechanism, or audio chatting sub-system. Those two improvement suggestions were indeed requested by 47% and 73% of the participants, respectively, as shown in the questionnaires in Appendix A, but that is out of the scope of this research and can be considered a good suggestion for future work.

The other two aspects of communication that showed no significant differences between the two conditions are *help initiation* and *help response*. Participants showed almost the same level of interest in asking for/offering assistance and responding to assistance requests. For *help initiation*, participants have asked for/offered help 0.75 and 0.78 times per minute in the co-located and distributed conditions, respectively. For *help response*, they have responded 0.73 and 0.64 times per minute in the co-located and distributed conditions, respectively. The difference between the number of initiations and responses is the ignored requests, which is higher in the distributed scenario. While participants have ignored less than 3% of assistance communication in the co-located scenario, they have ignored 18% in the distributed one. By referring to the participants answers in the questionnaires (Appendix A), it is noticed that they don't have any problem with assistance requests/offers, but 54% of them think that the messaging mechanism is not efficient. However, as presented previously in Subsection 5.3.2, the differences are statistically insignificant.

Webb [146] concluded that verbal help communication has a positive effect on participants achievement. It is obvious in this study that users prefer verbal communication for offering or asking for help; however, the effect of this preference on their efficiency and achievement will not be clear until the correlation analysis among all factors is discussed in Section 6.5 to see whether there is a significant correlation or not.

6.3.3 Contribution balance

RQ 2.3: *Does contribution balance differ between the co-located and distributed scenarios?*

The ability to synchronously accommodate multiple users is one of the major advantages of using mutli-touch tables for collaborative tasks. When more than one participant works on the same problem on the table, it is very important to analyse their contribution to the task to see whether they put in the same amount of effort or not. Such analysis has been done previously for participants in co-located condition for some other collaborative tasks; collaborative software design [14], for example. A similar contribution analysis has been carried out for both condition in Subsection 5.3.3, and the results will be discussed in this subsection. The aim of this part of analysis is to determine whether there is a difference in contribution balance between the two conditions.

Two aspects of participants contribution were taken into consideration in this research: *work contribution* and *communication contribution*. Work and communication are the two activities that participants were doing during the game in order to achieve the objective. Gini coefficient technique was used to measure equity of participation which is the factor to gauge the balance of participants contribution towards the given task: the more equal the participation the more balanced the contribution.

Harris et al. [56] method was followed to calculate the *work* and *communication* participation per minute for each participant under both conditions. For *work*, Gini coefficient technique was applied in order to measure the relative contribution of the individuals within each group in each condition. The results indicated that the equity of *work* participation in the co-located condition (mean= 0.21, sd = 0.03) was greater than that of the distributed condition (mean = 0.25, sd = 0.02) and the difference between the conditions was statistically significant based on the t-test. Figures 5.23 and 5.24 illustrate the proportion of the *work* contribution of the group members to the task and the groups relative Gini coefficient, respectively. As shown, in most cases, the equity of participation is more obvious in the co-located scenario than that in the distributed scenario.

A similar analysis has also been carried out to study the equity of *communication* participation. The results indicated that the equity of *communication* participation in the co-located condition (mean= 0.43, sd = 0.17) was less than that of the distributed condition (mean = 0.39, sd = 0.19), however, the difference between the conditions was statistically insignificant based on the t-test. Figures 5.25 and 5.26 illustrate the proportion of the *communication* contribution of the group members during the task and the groups relative Gini coefficient, respectively.

6.3.4 Summary

Research question (**RQ 2**) was about whether there are differences in COLLABORATION factors between both scenarios (see Section 5.3). As discussed in this section, differences were found in the *Styles*, *Communication*, and *Balance* factors. For the *Styles* part, there were significant differences in *VE* and *SGP* styles (**RQ 2.1**). In *Communication* part, the differences were found in *frequency*, *start time*, *interval*, and *response time* (**RQ 2.2**). The difference for the third factor, *Contribution Balance*, was found in equity of work participation (**RQ 2.3**). Differences in other sub-factors were statistically insignificant.

6.4 Usability

RQ 3: *Does system usability differ between the co-located and distributed scenarios?*

In this section, the results found in USABILITY analysis (Section 5.4) are discussed in order to understand the effects of distribution on the *Satisfaction*, *Ease of Use and Learn*, *Physical and Cognitive Demand* and internal correlations among the sub-factors. The research question is divided into four sub-questions according to the introduced aspects of USABILITY. By studying the results in Table 5.25, it is noticed that participant are *generally* satisfied with their experience with the system, found it easy to learn and use, and did not require high level of physical or cognition efforts. However, there were some differences between the two conditions, and that will be discussed in the following subsections.

6.4.1 Satisfaction

RQ 3.1: *Does satisfaction differ between the co-located and distributed scenarios?*

By studying the results of subject *satisfaction* differences in Subsection 5.4.2.1, it is clear that the participants were more satisfied with their experience with the application in the co-located scenario than that in the distributed scenario. *Satisfaction* is measured based on user's own earlier experience as suggested by Dix et al. [32] when they discussed the levels of usability measurements. The scores of *satisfaction* were calculated using the questionnaires completed by participants after they engaged in the experiment as shown in Section 5.4, this usability metrics was proposed in ISO standard 9241 [1].

The *satisfaction* score in co-located scenario (mean= 20.7, sd= 2.1) is higher than that in the distributed scenario (mean= 21.3, sd= 2.6), and the difference was statistically significant. Figure 5.27 illustrate this result. The major source of difference was that users were disappointed with the communication part in the distributed scenario, and they were not fully aware of each other's progress as shown in Table 5.26. The messaging communication mechanism, though very simple and efficient, lacks the ability to discuss strategy and plan as in verbal communication. Some of the participants have expressed that in their additional comments in the questionnaires as shown in Appendix A. For the awareness part, a more sophisticated system might help in maintaining the participants awareness of each other by implementing embodiment techniques, for example, which has proved an effective awareness mechanism as explained by Tang et al. [133].

6.4.2 Ease of use and learn

RQ 3.2: *Does ease of use and learn differ between the co-located and distributed scenarios?*

This aspect of USABILITY has also been studied in the same manner as *satisfaction*. Looking at the differences in the results of *ease of use and learn* in Subsection 5.4.2.2, it is clear that the difference is very small between the scores of the co-located scenario (mean= 34.4, sd= 4.6) and the distributed scenario (mean= 34.9, sd= 4.4), and in addition to that, this difference is statistically insignificant. Feng et al. [40, 39] described *ease of learn and use* as how easily an individual can learn to use a new application or complete a new task and how long they retained the learned skills. This aspect of usability is less studied than other aspects (Lazar et al. [78]). However, the ISO standard 9241 [1] usability metrics can also be applied here as well [32], as the scores of *ease of learn and use* were calculated using the questionnaires filled by participants after they engaged in the experiment as shown in Section 5.4. The results were illustrated in Figure 5.28. In general, participants found the application easy to use and the needed techniques were easy to learn in order to accomplish the given task in both conditions. That was clear in their answers in the questionnaires (see Appendix A).

6.4.3 Physical and cognitive demand

RQ 3.3: *Does physical and cognitive demand differ between the co-located and distributed scenarios?*

As in the previous two aspects of USABILITY, *physical and cognitive demand* has been analysed in Subsection 5.4.2.3 to find out the differences between the two conditions. This aspect, though less studied in HCI research, it plays an important role in technology adoption as stated by Lazar et al. [78]. As suggested by Dix [32], ISO standards 9241 for usability metrics [1] is used by examining the scores that were calculated using the questionnaires filled by participants after they engaged in the experiment as shown in Section 5.4. The results were illustrated in Figure 5.29. In general, participants did not find the application demanding a great deal of cognitive effort nor exerting abnormal physical fatigue in order to accomplish the given task in both conditions. Actually, they enjoyed the new experience, and in several occasions, they were happy and motivated to physically move around the tables and extend their arms and hands to reach farther parts of the work space as noticed later in the video recordings. The, relatively, strong and positive correlation between *satisfaction* and *physical and cognitive demand* supports this finding as well (see Subsection 6.4.4). Participants were a bit worried when they knew that the task involves solving mathematical questions, but they were relaxed when they understood the nature of the task and questions. That was clear in their answers in the questionnaires (see Appendix A).

Looking at the differences in the results of *physical and cognitive demand* in Subsection 5.4.2.3, it is clear that the difference is very small between the scores of the co-located scenario (mean= 14.8, sd= 2.8) and the distributed scenario (mean= 15.0, sd= 2.75), and in addition to that, this difference is statistically insignificant.

6.4.4 Correlations

RQ 3.4: *Do correlations among usability sub-factors differ between the co-located and distributed scenarios?*

In this subsection, and based on the correlation findings in Subsection 5.4.3.1 and Subsection 5.4.3.2, USABILITY sub-factors correlations are discussed for each scenario to understand the internal dynamics in the USABILITY side of the research.

It is noticed, in general, that the relationships among the USABILITY sub-factors follow a strong correlation pattern in both conditions, see Figures 5.30 and 5.31. Correlation coefficient between *satisfaction* and *ease of use and learn* are 0.77 and 0.65 for co-located and distributed conditions, respectively. This is an intuitive result as the easier to use and learn an application, the more satisfied the users are.

Coefficients between *satisfaction* and *physical and cognitive demand* are 0.48 and 0.49 for co-located and distributed conditions, respectively. This result may seem illogical at first, but as discussed in Subsection 6.4.3, participants were enjoying the challenge that the game was demanding. According to Bekker et al. [18], a successful computer game should be easy to learn at the beginning and challenging to achieve the goals. Players like to place themselves in challenging situations that increase their pleasure and satisfaction; an optimal gaming experience requires a balance between the perceived challenges and the skills of the user. A mismatch between the skills and the difficulty results in frustration (if it is too difficult) or boredom (if it is too easy) as explained by Csikszentmihalyi [29].

The last correlation coefficients are between *ease of use and learn* and *physical and cognitive demand*. r-coefficients are -0.58 and -0.67 for co-located and distributed conditions, respectively. This result is also an intuitive one; as the easier the application to learn and use the less cognitive effort it demands, and vice versa. That is why the relationship is inverted by a strong and negative correlation coefficient.

When these correlation coefficients were compared against each other for both scenarios in Subsection 5.4.3.3, the results showed that, statistically, there is no significant difference in application's USABILITY sub-factors relationships between the co-located and the distributed conditions.

6.4.5 Summary

Research question (**RQ 3**) was about whether there are differences in application's USABILITY factors between both scenarios (see Section 6.4). As discussed in this section, the differences were found only in the *satisfaction* factor (**RQ 3.1**). The differences in the other factors were statistically insignificant (**RQ 3.2**) and (**RQ 3.3**). Moreover, the differences in the correlation coefficients among those factors between both conditions were also statistically insignificant (**RQ 3.4**).

		r-coefficient	
Sub-factor 1	**Sub-factor 2**	**Co-located**	**Distributed**
Speed	CH Collaboration Style	-0.52	-0.48
Speed	VE Collaboration Style	-0.51	-0.46
Speed	SGP Collaboration Style	0.49	0.53
Added Difficulty	SSP Collaboration Style	-0.62	-0.21

Table 6.5 – PERFORMANCE and COLLABORATION correlation coefficients

6.5 Relationships In General

RQ 4: *Do the internal relationships among the HCI aspects differ between the co-located and distributed scenarios?*

In this section, the results found in general correlations analysis (Section 5.5) are discussed for two goals:

1. Understand the relationships between different aspects of the study in each condition
2. Find out whether there are differences in the correlation coefficients between the two conditions

Tables 5.32 and 5.33 present the strong correlation coefficients in both conditions, co-located and distributed. As mentioned previously in Subsection 5.5.1, only the strong and significant correlations were taken into consideration, other moderate, weak, or insignificant correlations were not studied as they should, statistically [41], have minimal effect.

6.5.1 Performance and collaboration relationship

RQ 4.1: *Do the internal relationships among the sub-factors of performance and collaboration differ between the co-located and distributed scenarios?*

Four correlation coefficients were found to be strong when the relationship between PERFORMANCE and COLLABORATION was analysed in Subsection 5.5.1. These results are summarised in Table 6.5

As shown, it is noticed that the PERFORMANCE is affected in its two factors: *Efficiency* (*speed*) and *Accuracy* (*added difficulty*). While COLLABORATION is affected in only one of its factors which is *Styles* (*CH*, *VE*, *SSP*, *SGP*). The relationship between different collaboration styles and collaborators performance has been studied previously in some other areas such as collaborative design tasks [13, 56, 64].

The relationship between *speed* and *CH style* is a negative one. When participants were performing at high speed, they often avoid communicating for help (*CH*), as they are deeply engaged in solving the problems in order to cover as much as they can before the link is reset (see Chapter 4). However, and as noticed in the video recordings, this strategy proved to be inefficient, and participants quickly discovered that they have to ask for/offer help to each other to achieve the common goal. When r-coefficient were compared in both conditions, the difference was statistically insignificant.

A similar conclusion can be withdrawn for the relationship between *speed* and *VE collaboration style* where the correlation is also negative. When a participant spent more time in *VE style* (viewing the workspace to think, plan, or see other's progress), he/she was not fully engaged in solving questions which means reduced speed. The difference between the r-coefficients in both conditions was statistically insignificant.

The relationship between *speed* and *SGP collaboration style* is positive. That is an intuitive results as the more the participants focus on the task the more speed they gain. The difference between r-coefficients in the two conditions was statistically insignificant.

Added difficulty affected *Accuracy* negatively as discussed in Subsection 6.2.2. It is the only aspect of *Accuracy* that has strong correlations with COLLABORATION aspects. Recall that *added difficulty* implies working on more links than the optimal needed links (see Subsection 5.2.2). Also, recall that *SSP collaboration style* is the time spent on working on the same link at the same time by both participants (see Subsection 5.3.1). The negative r-coefficient in the co-located scenario means that whenever the participants spent more time in *SSP style*, they were decreasing the difficulty of their solution of the game. This is a logical finding because *SSP style* means more closely coupled collaboration which assumes better coordination and cooperation between the collaborators [13, 64]. When the r-coefficients in both conditions were compared, the difference was statistically **significant**. The correlation in the co-located scenario is stronger than that in the distributed one, -0.62 and -0.21, respectively. That can be justified by knowing that *added difficulty* is more affected by other factors in the

		r-coefficient	
Sub-factor 1	**Sub-factor 2**	**Co-located**	**Distributed**
Incorrectness	Physical and cognitive demand	0.56	0.18

Table 6.6 – PERFORMANCE and USABILITY correlation coefficients

distributed condition than in the co-located one as shown in Subsection 5.2.3 where the correlations among all PERFORMANCE sub-factors were analysed. So, the *SSP style* has less effect on it in the distributed condition than that in the co-located condition.

6.5.2 Performance and usability relationship

RQ 4.2: *Do the internal relationships among the sub-factors of performance and usability differ between the co-located and distributed scenarios?*

Only one correlation coefficient was found to be strong when the relationship between PERFORMANCE and USABILITY was analysed in Subsection 5.5.1. This result is summarised in Table 6.6

The PERFORMANCE is affected in one of its factors which is the *Accuracy* (*incorrectness*). While USABILITY is affected in *physical and cognitive demand* factor. The level of accuracy and cognitive demand are closely related as discussed by Barnard et al. [12] and Militello et al. [85]. When an application demands high level of physical and cognitive efforts to be given by the users, it is expected that their accuracy will be adversely affected. In this research, one of the *Accuracy* sub-factors that were studied is the *incorrectness ratio*, which is the ratio of wrong answers that participants have given during the game. The correlation between *incorrectness ratio* and *physical and cognitive demand* sub-factors in this research conforms to the common understanding of this relationship as explained in previous studies [12, 85]. This result also supports the fact that awareness (which plays an important role *physical and cognitive demand* as shown by Paul et al. [106]) is highly correlated with *Accuracy*; that was discussed previously in Section 6.2.

It is noticed that the correlation between these two sub-factors is much stronger in the co-located condition than that in the distributed one, 0.56 and 0.18, respectively. That can be due to that both sub-factors are more affected by other sub-factors in the distributed condition than in the co-located condition (see Subsection 5.2.3.2 and Subsection 5.4.3.2).

		r-coefficient	
Sub-factor 1	**Sub-factor 2**	**Co-located**	**Distributed**
Help Initiation	Phys. & Cog. Demand	-0.40	-0.57
Response Time	Phys. & Cog. Demand	-0.13	-0.61
Work Cont. Balance	Satisfaction	0.69	0.45

Table 6.7 – COLLABORATION and USABILITY correlation coefficients

However, when both correlations were examined for difference (Subsection 5.5.1), the result was statistically insignificant.

6.5.3 Collaboration and usability relationship

RQ 4.3: *Do the internal relationships among the sub-factors of collaboration and usability differ between the co-located and distributed scenarios?*

Three correlation coefficients were found to be strong when the relationship between COLLABORATION and USABILITY was analysed in Subsection 5.5.1. These results are summarised in Table 6.7

The COLLABORATION factors that were affected by this relationship are: *Communication* (*help initiation* and *response time*) and *Contribution Balance* (*work*). While USABILITY is affected in *Satisfaction* and *Physical and cognitive demand* factors.

Correlation coefficients between *help initiation* and *physical and cognitive demand* followed the same negative pattern and were -0.40 and -0.57 for co-located and distributed conditions, respectively. Webb et al. [146, 148] have shown positive effects of help behaviour on participants cognitive performance. The more assistance offered and accepted, the less physical and cognitive demand the task exerts on them. The results of this study conform to those findings; as it is noticed that participants seemed to be more comfortable with the given task when they assist each other. Although the relationship shows only the *help initiation* sub-factor, the other part of the assistance mechanism, *help response*, is, generally, implied as shown in Subsection 6.3.2. Also, notice that *physical and cognitive demand* has the same correlation pattern with *response time*, which, clearly, supports the previous argument. When r-coefficients were compared between both conditions, the differences were statistically insignificant.

The relationship between work contribution balance and satisfaction is intuitive. Many studies have shown that distribution of work and equity of participation play a great role in satisfaction, see Rodwell and Reinig [111, 109] for example. Reinig [109] has shown that the use of collaborative technologies that help team members to participate in the task increase the rate of their satisfaction. Rodwell [111] found that the more the task is distributed among participants the more satisfied they are. Findings in this research are very similar to what have been proposed by previous work. There is a positive relationship between *work contribution balance* and *satisfaction* with correlation coefficients of 0.69 and 0.45 in co-located and distributed scenarios, respectively. Although the r-coefficient shows a stronger correlation in the co-located condition, the differences were statistically insignificant. The reason for this is that work equity of participation and satisfaction ratio were higher in the co-located scenario than that in the distributed scenario.

6.5.4 Summary

Research question (**RQ 4**) was about whether there are differences between co-located and distributed scenarios in the relationships among the three areas of the research, PERFORMANCE, COLLABORATION, and USABILITY. The correlation analysis between PERFORMANCE and COLLABORATION sub-factors showed that there was a significant difference between the two conditions in the relationship between *Accuracy* (*added difficulty*) and *Collaboration Styles* (*SSP*), with no significant differences found between other sub-factors (**RQ 4.1**). The differences for the other areas: PERFORMANCE and USABILITY (**RQ 4.2**), and COLLABORATION and USABILITY (**RQ 4.3**), were statistically insignificant.

6.6 Chapter Summary

In Chapter 6, the results of data analysis that has been carried out in Chapter 5 were discussed. A briefing of the hypotheses tests was introduced at the beginning of the chapter (Section 6.1), then the research questions were structurally presented in order to discuss their related results and answer them.

In the area of PERFORMANCE, there were significant differences in the *Efficiency* factor (Section 6.2). In COLLABORATION area, the differences were in *Collaboration Styles*, *Communication*, and *Work Contribution Balance* factors (Section 6.3). A difference in user *Satisfaction* factor was found in the USABILITY area (Section 6.4). And finally, the differences between the two conditions for the correlations among the three areas were discussed; the differences were insignificant with an exception of two sub-factors in PERFORMANCE and COLLABORATION (Section 6.5).

In the next chapter, conclusions and contributions of this research work are presented, along with recommendations and guidelines that can help later for designing such systems. Suggestions for future work and continuation to this research are also presented.

7 Conclusions

This chapter summarises the conclusions of this research on the effects of multi-touch users distribution on the HCI aspects of performance, collaboration, and usability. It presents the implications of the results that have been found and discussed in Chapters 5 and 6. It also highlights the contributions of this study to research into HCI and distributed users applications, as well as some potential effects on relevant software design practices. The limitations of the study are briefed; then finally, suggestions of future research work in this field are presented.

7.1 Investigation Implications

A number of research questions were proposed early in Chapter 1 (Subsection 1.4.1); the success of this research can be measured in terms of providing answers to these questions. In Chapters 5 and 6, the questions have been investigated in great detail. In this section, the implications of the answers to these questions are presented for each area of the study.

7.1.1 Performance

The results reported and discussed in Chapters 5 and 6 showed that users (players), generally, have the same level of performance in both scenarios. Users could perform the given task with less time and effort in the co-located scenario, although they were working at a higher speed in the distributed scenario. This gives an indication that, in such type of collaborative applications, the measurement of efficiency is more reliable when total time and total work are taken into consideration rather than depending only on the speed of the users actions.

The accuracy of task results were comparable in both scenarios. This conclusion can be drawn for similar collaborative work tasks that involve mathematical problems within a maze game. As shown in Section 5.5, accuracy has a strong correlation with communication, which can lead to the conclusion that the distributed scenario configuration was successful in providing a collaborative environment that helped the users in achieving accurate results as in the co-located scenario.

This research, also, identified an important implication of high efficiency and accuracy, that is *awareness*. Gutwin et al. [52] showed that there is a strong correlation between efficiency and accuracy on one side and awareness of the workspace on the other. The results presented in Chapter 5 showed, generally, a higher rate of efficiency and accuracy in the co-located scenario than that in the distributed scenario, which implies a higher sense of awareness. This result conforms to some of the previous studies of awareness in distributed tabletops environments (e.g. Tuddenham and Robinson [140]).

7.1.2 Collaboration

This research identified clear differences in the three sub-areas of collaboration. Firstly, for the collaboration styles, results presented in Chapter 5 showed that users spent more time in close collaborative styles in the co-located scenario than that in the distributed one. On the other hand, they spent more time in loose collaborative styles in the distributed scenario. Previous works have concluded that close collaboration styles should be encouraged more than loose collaboration styles [64, 13], however, it is expected that users tend to collaborate loosely more than closely in the distributed scenario as illustrated in this thesis. A more engaging communication and awareness mechanism, such as audio/video chatting, in the distributed condition will have great advantage on the whole experience.

Secondly, for the communication part of collaboration; the implemented system should provide an effective communication mechanism for the users in the distributed scenario [81]. Based on the results in Chapter 5, the users should be able to convey their messages in the shortest time with the least effort. They should, also, start to communicate as soon as possible once they start the task, and they should stay in contact for the longest time during the work session. Taking these points into consideration will greatly help in making communication as effective as possible, which will have a significant positive effect on the whole collaborative work experience [52, 147].

And, finally, for the contribution balance side of collaboration; this research found that users work contribution is more balanced in the co-located scenario. Being co-located make it easier and more natural for users to coordinate the work balance which is a desired objective in collaborative work in general [14]. Implementing an automated task distribution function in the application can help the users in achieving the work contribution balance objective, taking into consideration that this function must not add to the complexity of the main task given to the users. Another choice is by adding this coordination function to the communication system, and train the users to assign parts of the task between them accordingly. Actually, this feature was asked for by some participants in the survey after the experiment, however, such an addition must be designed carefully as it may complicate the communication system which is assumed to be an easy and effective system to use as described in Chapter 6.

7.1.3 Usability

Users showed a higher satisfaction level in the co-located scenario than that in the distributed scenario. As the usability analysis showed in Chapter 6, the major concern of the users was their inability to effectively communicate and coordinate work in the distributed condition. Although, this concern did not severely affect their total performance or collaboration level, it negatively affected their satisfaction with the user experience in the distributed scenario. Implementing a more sophisticated communication and coordination system for users in the distributed condition may help them in achieving higher engagement which will lead to a higher satisfaction level. However, and as previously mentioned, these additional options must be designed carefully to ensure that they will not obstruct the users main focus nor add more complexity to the given task, which may have a negative impact on the users performance.

7.2 Contributions of Thesis

The main contribution of this research was to show the effects of the users physical location on three HCI related areas within the context of multi-player games on multi-touch tabletops. Although this topic has been studied in some previous research, typically it was considered in the context of traditional collaborative work, such as information sharing [140, 155] and information visualisation [10, 11]. The gaming environment introduce other interesting factors that affect the whole collaboration experience [81], such as challenges, enjoyment, and time constraints.

The results generated from this research add to the current knowledge of HCI factors in multi-player games over the promising technology of multi-touch tabletops. Application designers can benefit from these results when they consider the user's location condition. For example, Dix et al. [32] recommends the use of usability specifications as a means of requirements specifications for any software that involves significant HCI aspects. The analysis framework that has been developed during the course of this study can be reused to extend the findings related to the topic, or can be adopted by other fields other than games. The statistical procedures used to develop this framework are robust and well used in scientific experimental research.

7.2.1 Impacts on tabletop interface software design

The results presented in this thesis can assist in suggesting some useful recommendations for software designers in designing and implementing collaborative software environments for tabletops. Moreover, such recommendations can help researchers in extending the ideas presented in this thesis for building applications for new similar research works.

In addition to that, the observation of the users during the experimental phase of this research and how did they interact with the system and with each other is a very rich source of information that helped in forming the following recommendations for designers and developers of collaborative software environments for multi-touch tables.

Recommendation 1: *Follow a minimalist approach in designing the user interface*

Because of the large surface area, tabletops have, genuinely, very large workspaces that can easily accommodate users artefacts and interactions. As many users can work together synchronously, different objects and parts of the user interface may get lost or unintentionally hidden by others objects, which may negatively affect the user experience with such applications. Keeping the interface as simple as possible and using some techniques for workspace organisation, such as territoriality [140, 99], will definitely help users to manage their artefacts collaboratively. In the application used for this research, the elements of the interface were clearly defined with each user has his/her own area of work (see Chapter 4).

Recommendation 2: *Use interaction styles that facilitate navigation between different areas of the interface*

Frequently extending hands to reach far parts of the tabletop interface may disappoint users and add to their work load and fatigue. As the research of Nacenta et al. [98] points out, the easier the users can reach different areas of the interface the higher their satisfaction with the application. In the application built for this research, when a player confirms an assistance request from the other player in the distributed scenario, his/her panel is automatically connected to the link in concern. Users liked this functionality more than having to manually connect their panels to the links as in the co-located scenario (panels and links were described in Chapter 4).

Recommendation 3: *Implement awareness enhancement techniques*

Awareness can be enhanced by a clear definition of different parts of the workspace, a simple and effective communication mechanism, and by displaying clear notifications to the users (for example, to inform them about their progress and system state). By considering these enhancements when implementing a collaborative system, the awareness problems in groupware workspaces, described by Gutwin et al. [52], can be minimised. In the system used in this research, workspace's parts were clearly defined, and the notifications displayed for users were emphasised and easy to read (refer to Chapter 4).

Recommendation 4: *Simulate real life physical tables and objects by facilitating digital artefacts manipulation*

Users can naturally move around the table to find the location that suits their preference and area of work (Figure 4.1). Digital artefacts displayed on top of the multi-touch surface should be easily rotated and moved around (e.g. the player's panel in this research). The user experience can be more natural and smoother by making the interaction with tabletops and digital objects similar to real physical tables and artefacts, which plays an important role in collaborative work and sense of awareness as shown by Kruger et al. [75, 74].

Recommendation 5: *Consider the technical specifications and limitations of the tables before implementation*

As any other framework, multi-touch tabletops have some limitations. The designer of the software must be aware of these limitations in order not to jeopardise the objectives of the research due to unmanageable technical difficulties. These limitations include: the underlying operating system capabilities, the framework specifications, number of simultaneous multi-touches, and computationally expensive gestures. For example, it was not feasible to implement some visual features in this research's software due to the framework specifications. Richardson et al. [110] explained in depth how these technical aspects can be managed with focus on the SynergyNet framework [3] used in this research.

7.3 Limitations of Study

As with any research that involves user study, there are some limitations of this research work in addition to the threats to validity which were discussed previously in Section 3.6. Personal differences between participants could be a source of variation in the results. These differences include gender, age, motivation, and educational level. While every effort has been made to reduce the impact of these differences, nevertheless they may have had an impact on the results.

Finding enough people to participate in the experimental work is extremely difficult especially that each experiment session needs two participants. Therefore, other scenarios that need more than two people per session where omitted in this research. Also, there could be more complicated scenarios where more than two tables are connected together. This option has also been dropped because of the limited number of available tables at the time of the experiment.

During the experiment in the co-located condition, the only oral communication that were considered is the communication for assistance. Other types of talk, such as planning or arguing, were not considered. This is because of the limitation in the distributed condition which implements only the assistance part of communication. Other communication types could be considered in future work as shown in the next section.

Another limitation is in the multi-touch tabletops themselves. The available tables were limited to a certain framework developed by TEL[1] team, which may make the integration with other software resources a complicated process. Also, these tables run in low resolution setting[2] which makes text reading problematic in some situations.

7.4 Future Work

The following points summarise some suggestions for future work that may extend the current thesis or build on it.

- More than two players: a lot of traditional multi-player games can accommodate many players playing at the same time. A proposal for four, six, and eight players was in the original plan for this research. However, due to the limitations of the number of participants, only the basic two players scenario was considered.

- More than two tables: as in the previous point, the suggestion of using up to four tables was in the original plan. This can extremely enrich the scenarios by dividing the users into teams for example.

- More complex game scenarios: although the study of the games by themselves is not an objective of this research, this option can add to the knowledge of the gaming community and application designers who might be interested in building games for the multi-touch surfaces platforms.

- Analyse panels translation and rotation: the artefacts location and orientation have been analysed in many previous studies. This is also applicable in this research for the panels components which can be freely rotated and translated according to the

[1] Technology Enhanced Learning research group, Durham University.

[2] 1024 x 768.

user's preference. The results of such an anlysis might help in determining players favourite setup of the user interface components as well as defining the hot zones of the workspace where users do most of their work.

- Other games genres: the game used in this research belongs to the "maze" genre of games. There could be some interesting findings if the idea of the research is applied on other genres such as "role-playing" or "strategy-planning".

- Different communication systems: more sophisticated communication mechanisms can be implemented and added to the experience. This may include audio, video, or text chatting. A comparison between the effectiveness of different communication systems can be a very valuable source of information.

- Extending the current messaging system: by enabling the users in the distributed scenario to communicate for strategy planning, suggestions, and decision making. As mentioned in the limitations section, only the communication for assistance is considered in this research. The addition of other types of communication will greatly affect the game experience.

- Real networking game: as mentioned in the assumptions section in Chapter 1, this research does not study the networking techniques and their implications on the application performance and usability. Hence, the addition of this factor to the analysis of HCI aspects will reveal new findings that could be of interest.

- Study participants demography: it was assumed that the demography parameters are not considered in this research. Studying the effects of such factors (gender, age, education, etc.) can add to the value of the results, especially that usability studies are very interested in demography findings.

- Provide more than one theme of questions: the questions presented to the players in the game were all extracted from a pool of mathematical questions (basic mathematical operations). Providing other type of questions from other fields, such as geography, history, science, etc., can open a new dimension for the results analysis especially from the educational point of view.

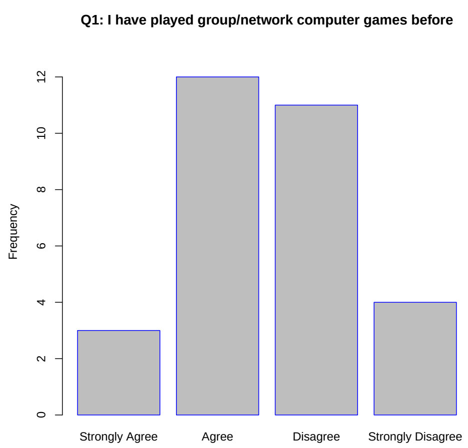
A Detailed Questionnaires Results

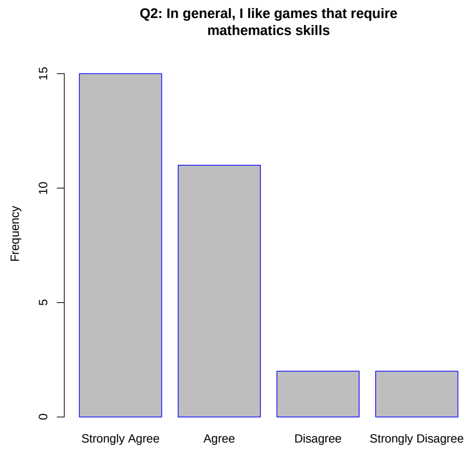
A.1 General Questions

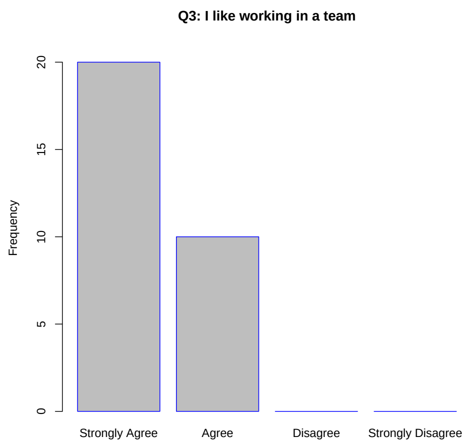
Note: **SA**= Strongly Agree, **A**= Agree, **D**= Disagree, **SD**= Strongly Disagree

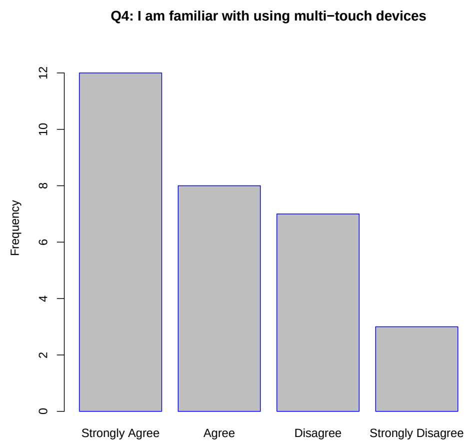
	Question	SA	A	D	SD
Q.1	I have played group/network computer games before	3	12	11	4
		10%	40%	37%	13%
Q.2	In general, I like games that require mathematics skills	15	11	2	2
		50%	37%	7%	7%
Q.3	I like working in a team	20	10	0	0
		67%	33%	0%	0%
Q.4	I am familiar with using multi-touch devices	12	8	7	3
		40%	27%	23%	10%
Q.5	I quickly understood how to interact with the interface	18	12	0	0
		60%	40%	0%	0%
Q.6	The displayed information was easy to read	20	10	0	0
		67%	33%	0%	0%
Q.7	The organisation of information on the display surface was clear	20	10	0	0
		67%	33%	0%	0%

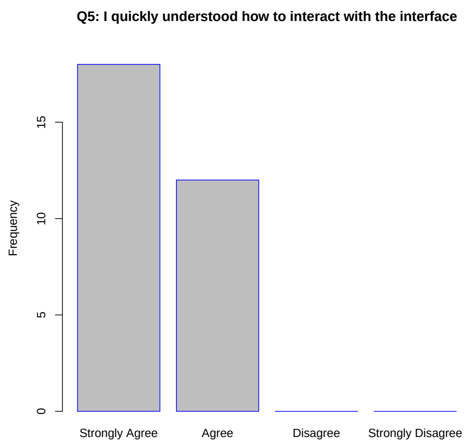
	Question	SA	A	D	SD
Q.8	Connecting links to panels by dragging lines was easy to do	6	16	7	1
		20%	53%	23%	3%
Q.9	Overall, I am satisfied with how easy it is to use the multi-touch interface	16	14	0	0
		53%	47%	0%	0%
Q.10	I enjoy working with a remote team-mate more than a nearby one	2	5	13	10
		7%	17%	43%	33%
Q.11	The physical absence of my team-mate affected my performance negatively	5	12	8	5
		17%	40%	27%	17%
Q.12	I did not like being asked for help from my team-mate	0	0	20	10
		0%	0%	67%	33%
Q.13	I would like to have text chatting feature with my team-mate	2	12	13	3
		7%	40%	43%	10%
Q.14	I would like to have voice communication feature with my team-mate	7	14	8	1
		23%	47%	27%	3%
Q.15	In general, it was easier to work alone on the table without somebody else next to me	1	10	16	3
		3%	33%	53%	10%
Q.16	I found the messaging buttons more efficient in communicating with my team-mate	4	10	8	8
		13%	33%	27%	27%

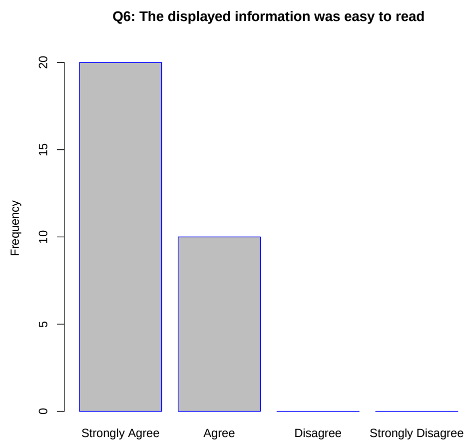

Q1: I have played group/network computer games before
Frequency
0
2
4
6
8
10
12
Strongly Agree
Agree
Disagree
Strongly Disagree

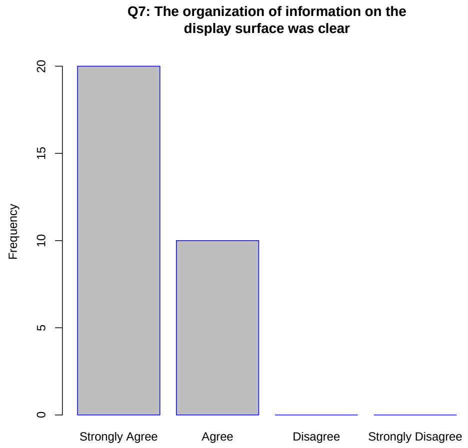

Q2: In general, I like games that require mathematics skills
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree

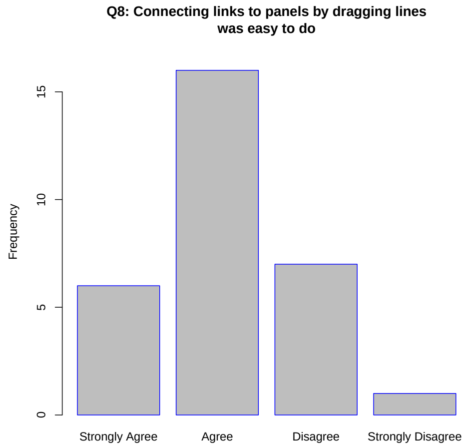

Q3: I like working in a team
Frequency
0
5
10
15
20
Strongly Agree
Agree
Disagree
Strongly Disagree

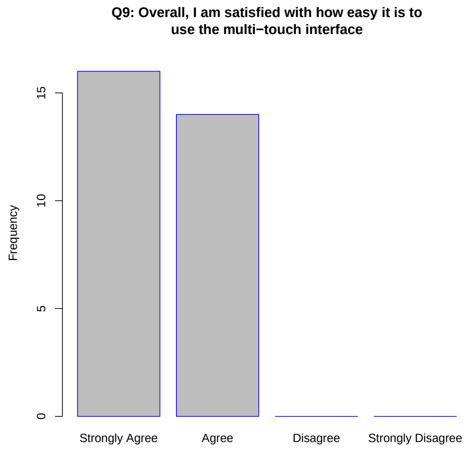

Q4: I am familiar with using multi−touch devices
Frequency
0
2
4
6
8
10
12
Strongly Agree
Agree
Disagree
Strongly Disagree

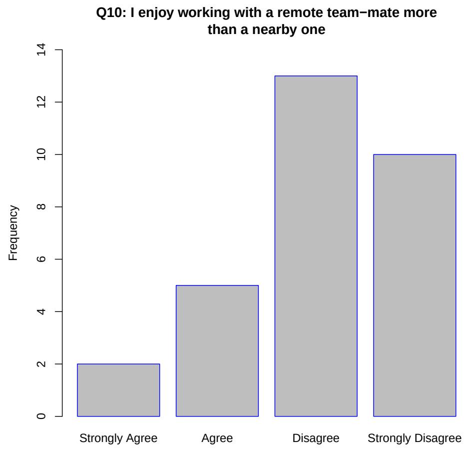

Q5: I quickly understood how to interact with the interface
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree

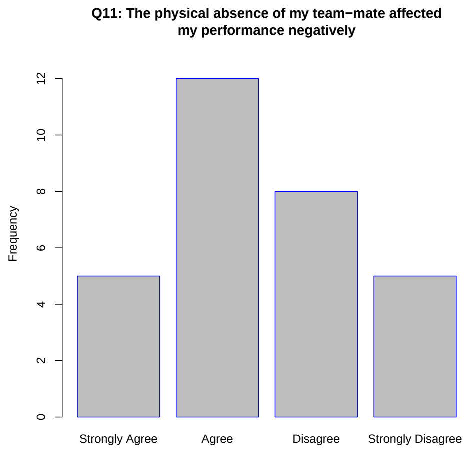

Q6: The displayed information was easy to read
Frequency
0
5
10
15
20
Strongly Agree
Agree
Disagree
Strongly Disagree

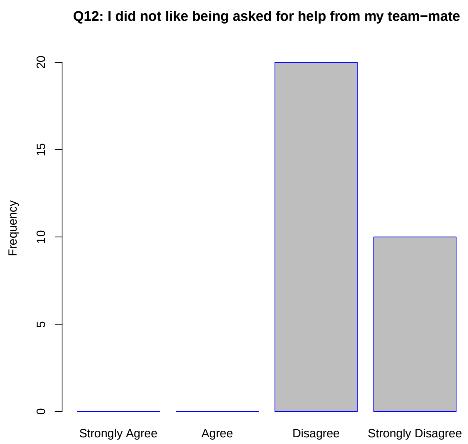

Q7: The organization of information on the display surface was clear
Frequency
0
5
10
15
20
Strongly Agree
Agree
Disagree
Strongly Disagree

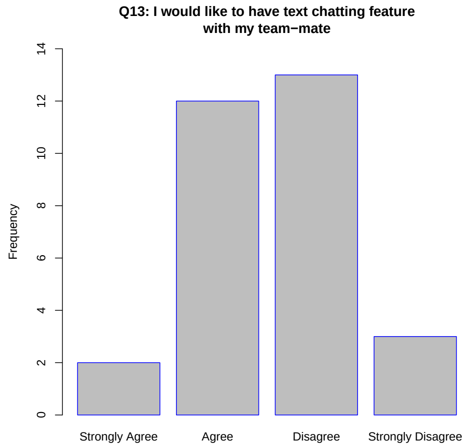

Q8: Connecting links to panels by dragging lines was easy to do
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree

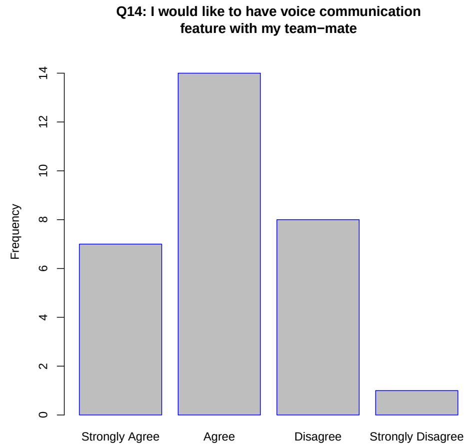

Q9: Overall, I am satisfied with how easy it is to use the multi−touch interface
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree

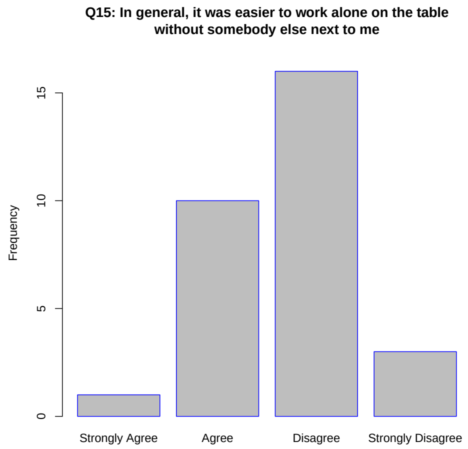

Q10: I enjoy working with a remote team−mate more than a nearby one
Frequency
0
2
4
6
8
10
12
14
Strongly Agree
Agree
Disagree
Strongly Disagree

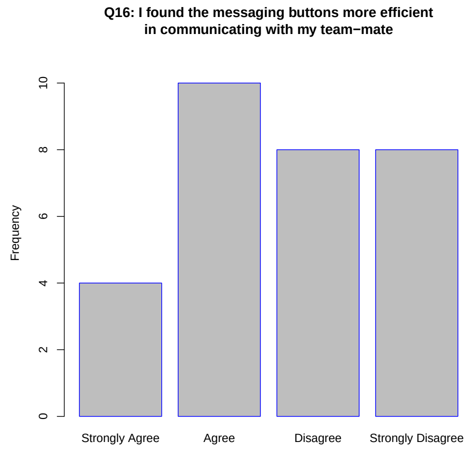

Q11: The physical absence of my team−mate affected my performance negatively
Frequency
0
2
4
6
8
10
12
Strongly Agree
Agree
Disagree
Strongly Disagree


Q12: I did not like being asked for help from my team−mate
Frequency
0
5
10
15
20
Strongly Agree
Agree
Disagree
Strongly Disagree


Q13: I would like to have text chatting feature
with my team−mate
Frequency
0
2
4
6
8
10
12
14
Strongly Agree
Agree
Disagree
Strongly Disagree


Q14: I would like to have voice communication
feature with my team−mate
Frequency
0
2
4
6
8
10
12
14
Strongly Agree
Agree
Disagree
Strongly Disagree

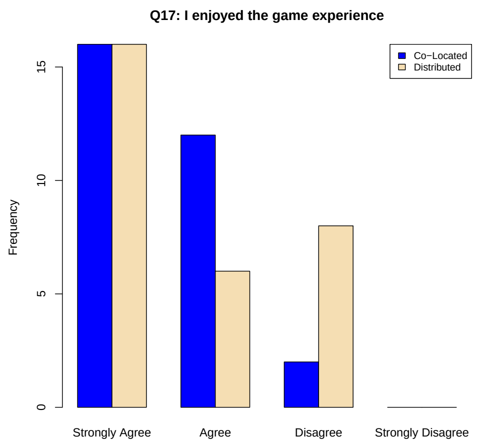

Q15: In general, it was easier to work alone on the table
without somebody else next to me
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree

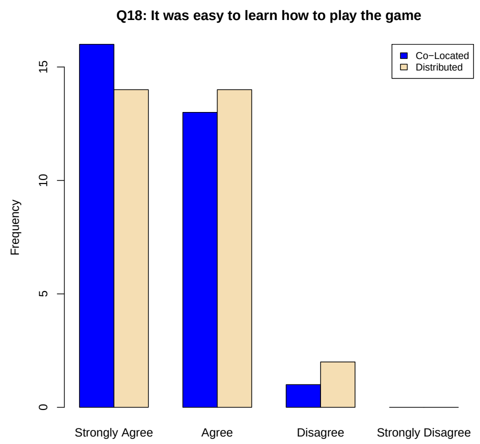

Q16: I found the messaging buttons more efficient
in communicating with my team−mate
Frequency
0
2
4
6
8
10
Strongly Agree
Agree
Disagree
Strongly Disagree

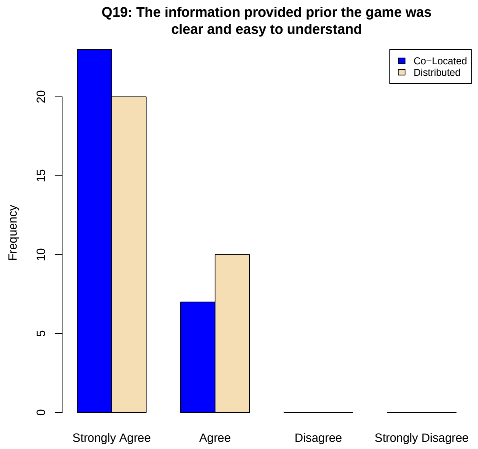
A.2 Comparative Questions

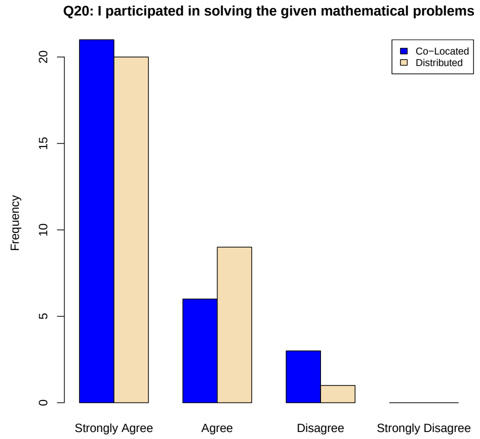
Note: **SA**= Strongly Agree, **A**= Agree, **D**= Disagree, **SD**= Strongly Disagree

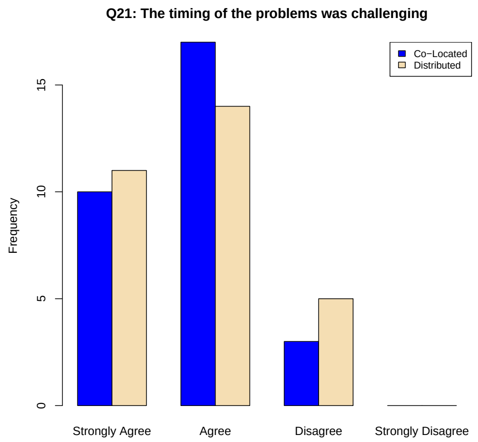
		Co-located				Distributed			
	Question	**SA**	**A**	**D**	**SD**	**SA**	**A**	**D**	**SD**
Q.17/30	I enjoyed the game experience	16	12	2	0	16	6	8	0
		53%	40%	7%	0%	53%	20%	27%	0%
Q.18/31	It was easy to learn how to play the game	16	13	1	0	14	14	2	0
		53%	43%	3%	0%	47%	47%	7%	0%
Q.19/32	The information provided prior the game was clear and easy to understand	23	7	0	0	20	10	0	0
		77%	23%	0%	0%	67%	33%	0%	0%
Q.20/33	I participated in solving the given mathematical problems	21	6	3	0	20	9	1	0
		70%	20%	10%	0%	67%	30%	3%	0%
Q.21/34	The timing of the problems was challenging	10	17	3	0	11	14	5	0
		33%	57%	10%	0%	37%	47%	17%	0%
Q.22/35	I found it easy to get involved in the activity	21	9	0	0	15	15	0	0
		70%	30%	0%	0%	50%	50%	0%	0%
Q.23/36	The game encourages working together like a team	23	7	0	0	19	7	4	0
		77%	23%	0%	0%	63%	23%	13%	0%
Q.24/37	I frequently offered help to my team-mate	10	18	2	0	9	15	5	1
		33%	60%	7%	0%	30%	50%	17%	3%
Q.25/38	I frequently asked for help from my team-mate	9	19	2	0	13	13	4	0
		30%	63%	7%	0%	43%	43%	13%	0%
Q.26/39	I found the game easy to play without helping each other as a team	4	9	14	3	3	11	14	2
		13%	30%	47%	10%	10%	37%	47%	7%
Q.27/40	I was aware of my team-mate work and progress	11	17	2	0	9	18	2	1
		37%	57%	7%	0%	30%	60%	7%	3%
Q.28/41	I frequently moved and rotated my panel in order to suit the location of work	5	12	9	4	3	16	9	2
		17%	40%	30%	13%	10%	53%	30%	7%
Q.29/42	It was easy to interact with the game from any position around the table	14	15	1	0	11	19	0	0
		47%	50%	3%	0%	37%	63%	0%	0%

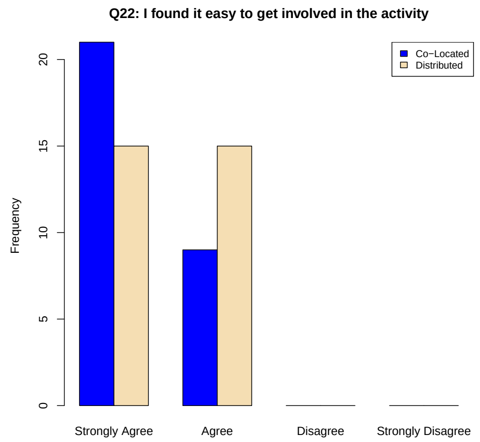

Q17: I enjoyed the game experience
Co−Located
Distributed
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree

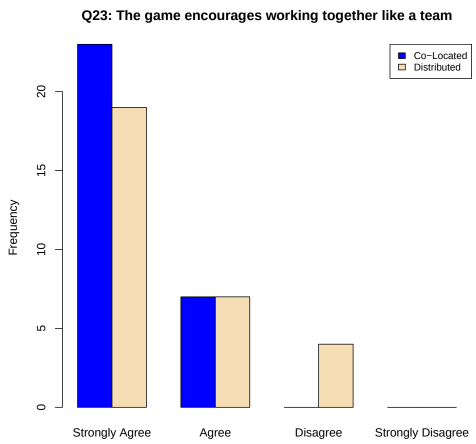

Q18: It was easy to learn how to play the game
Co−Located
Distributed
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree

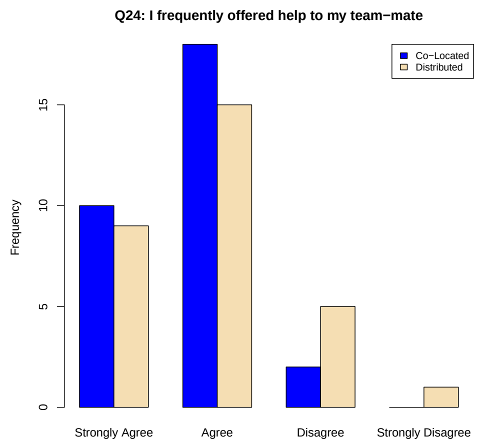

Q19: The information provided prior the game was clear and easy to understand
Co−Located
Distributed
Frequency
0
5
10
15
20
Strongly Agree
Agree
Disagree
Strongly Disagree

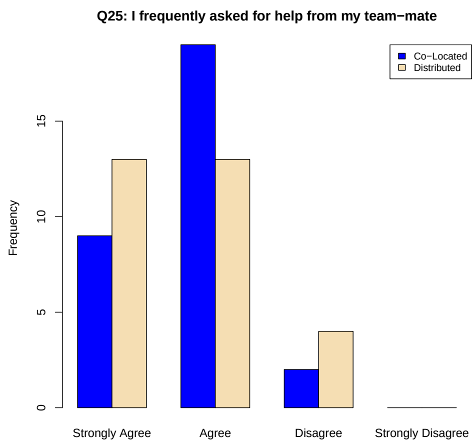

Q20: I participated in solving the given mathematical problems
Co−Located
Distributed
Frequency
0
5
10
15
20
Strongly Agree
Agree
Disagree
Strongly Disagree

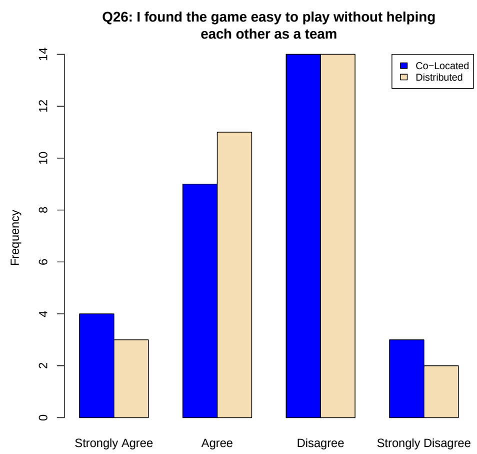

Q21: The timing of the problems was challenging
Co−Located
Distributed
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree

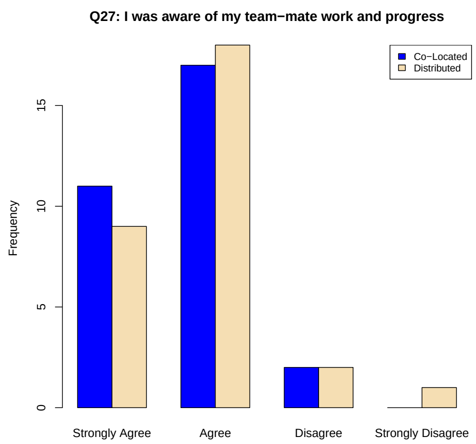

Q22: I found it easy to get involved in the activity
Co−Located
Distributed
Frequency
0
5
10
15
20
Strongly Agree
Agree
Disagree
Strongly Disagree

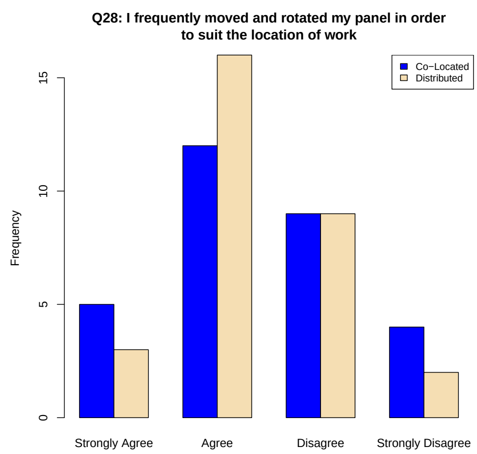

Q23: The game encourages working together like a team
Co−Located
Distributed
Frequency
0
5
10
15
20
Strongly Agree
Agree
Disagree
Strongly Disagree

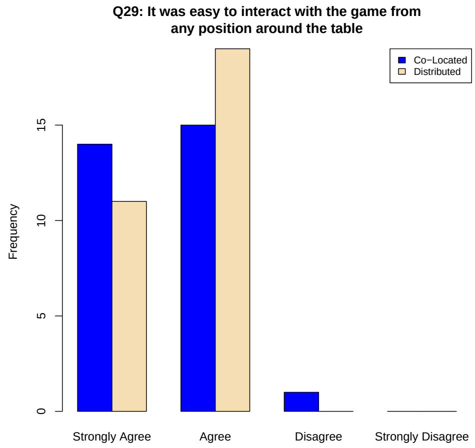

Q24: I frequently offered help to my team−mate
Co−Located
Distributed
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree


Q25: I frequently asked for help from my team−mate
Co−Located
Distributed
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree


Q26: I found the game easy to play without helping
each other as a team
Co−Located
Distributed
Frequency
0
2
4
6
8
10
12
14
Strongly Agree
Agree
Disagree
Strongly Disagree


Q27: I was aware of my team−mate work and progress
Co−Located
Distributed
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree


Q28: I frequently moved and rotated my panel in order
to suit the location of work
Co−Located
Distributed
Frequency
0
5
10
15
Strongly Agree
Agree
Disagree
Strongly Disagree



A.3 Participants Additional Notes

In addition to answering the questions after the experiment sessions, participants wrote down some notes and comments on their experience with the application. Their points are quoted below.

- I really like the experiment. It make the team work more funny and interactive, where you can see other team-mate work.
- I didn't try moving around the table and it was fine from the right side position I was in at the table. In general: good explanation, fun activity.
- I found it a bit uncomfortable to work individually. I prefer the first experiment (co-located). There are more communication verbally on first experiment that make us work more efficiently. There were some silence communication through the panels, where we can watch them working on something and that make us work on something else. It was really exciting experiment.
- Thanks, I enjoyed the experiment.
- Sometimes I had to press the answer more than once to get any response.
- Might be easier if had text communication to decide strategy before starting.
- Panel moved around on its own, so I needed to move it back. And if you're trying to work together, but sit alone, it is more difficult because asking the other person if they need help is distracting to them.

- I like the interactive and high resolution of the game. Interesting and attractive. All is good.
- Enjoyed.
- The table was a little big so while I was working on a problem, it was hard to see my progress across the table. Also my team-mate progress. The only reason I think it would be necessary to perhaps communicate verbally/chat is to discuss a strategy of attacking the nodes.
- Enjoyable experience. Challenging. Good motivation for learning and being engaged with the task. Well designed. I would prefer working and speaking with my team-mate to be more productive, feel more confident, and it could make it even more enjoyable.
- The touch screen seemed unresponsive at times.
- The time provided was short to solve the questions.
- Only at the end did I figure out it was easier to solve the problems with the help of a team-mate. Instructions by the researcher were clear but written instructions on the dragging and asking for help might be useful to some users who tend to forget verbal instructions.
- This is a really nice experience to play games with your mates on multitouch screens. It is very helpful to do multitasking quickly and efficiently.
- It was good fun and a good way of making people work as a team because it would not have been possible to complete without help from the other person.
- Fun and interesting tool. The only issue I had was dragging the lines from the links to my display box.
- A web cam feature may have been helpful to make you feel more part of a team when working on separate tables.
- This is more challenging, however, less interesting.
- It was much easier to plan strategies with the ability to communicate verbally.
- I enjoyed that I could ask questions my team-mate in co-located scenario, I had more fun this time than working alone and I could follow my team-mate progress easily.
- Sometimes the table didn't pick up my touches.
- Being next to team-mate makes it more enjoyable but is not related to the game.
- I did not move around much because the multitouch screen allowed me to work from the same spot, hence the lack of moving around, so to me it was easy without having to move here and there.

- Well, this is quite nice experience to play games and perform multitasking on multitouch screen.
- I think that working in a team gives a greater sense of efficiency and achievement that could be exceptionally useful in a learning situation and also helps facilitate communication. Again a similar comment about ease with when the arrows could be dragged.
- It is good how the tables do not have to be displayed at right angles or do not automatically adjust to such being able to place them wherever and at whatever angle is preferable on the tablet was really good. Working alongside my team mate physically and being able to communicate made the whole experience so much more enjoyable.

B Questionnaires

Two sets of questionnaires were used in this study, and they can be distinguished by the label in their titles:

1. Questionnaires for participants who did the co-located scenario first are labelled (**COL-DIS**)
2. Questionnaires for participants who did the distributed scenario first are labelled (**DIS-COL**)

These questionnaires are included in the following pages of this appendix.

Math Race on Multi-Touch Surfaces (COL-DIS)

Questionnaire: ***Co-Located***

All given information is strictly confidential

Name:

Date:

Please tick [✔] the appropriate column that indicate your agreement level with the following statements:

	Statement	Strongly Agree	Agree	Disagree	Strongly Disagree
1	I enjoyed the game experience				
2	It was easy to learn how to play the game				
3	I have played group/network computer games before				
4	The information provided prior the game was clear and easy to understand				
5	In general, I like games that require mathematics skills				
6	I participated in solving the given mathematical problems				
7	The timing of the problems was challenging				
8	I found it easy to get involved in the activity				
9	The game encourages working together like a team				
10	I frequently offered help to my team-mate				
11	I frequently asked for help from my team-mate				
12	I like working in a team				
13	I found the game easy to play without helping each other as a team				
14	I was aware of my team-mate work and progress				
15	I frequently communicated verbally with my team-mate				

	Statement	Strongly Agree	Agree	Disagree	Strongly Disagree
16	I have used a multi-touch device before				
17	I quickly understood how to interact with the interface				
18	The displayed information was easy to read				
19	The organization of information on the display surface was clear				
20	Connecting links to panels by dragging lines was easy to do				
21	I frequently moved and rotated my panel in order to suit the location of work				
22	It was easy to interact with the game from any position around the table				
23	I know my team-mate prior to this experiment	YES		NO	

Age: ☐ ***Sex***: Female ☐ Male ☐

Education Level: High School ☐ College ☐ Postgraduate Degree ☐

Finally, could you please write down any further comments, positives, and negatives that you would like the researcher to know about your experience in this study:

Thank you very much

Math Race on Multi-Touch Surfaces (COL-DIS)

Questionnaire: ***Distributed***

All given information is strictly confidential

Name:

Date:

Please tick [✔] the appropriate column that indicate your agreement level with the following statements:

	Statement	Strongly Agree	Agree	Disagree	Strongly Disagree
1	I enjoyed the game experience in distributed setup more than being with my team-mate on the same table				
2	I felt comfortable playing the game in distributed setup				
3	The information provided prior to this stage of the game was clear and easy to understand				
4	I participated in solving the given mathematical problems				
5	The timing of the problems was challenging				
6	I found it easy to get involved in the activity				
7	The game encourages working together				
8	I frequently offered help to my team-mate				
9	I frequently asked for help from my team-mate				
10	I enjoy working with a remote team-mate more than a nearby one				
11	I found the game easy to play without the help of my team-mate				
12	I was aware of my team-mate work and progress				
13	I found the messaging buttons more efficient in communicating with my team-mate				
14	The physical absence of my team-mate affected my performance negatively				
15	I did not like receiving messages asking for help from my team-mate				
16	I would like to have text chatting feature with my team-mate				
17	I would like to have voice communication feature with my team-mate				

	Statement	Strongly Agree	Agree	Disagree	Strongly Disagree
18	Overall, I am satisfied with how easy it is to use the multi-touch interface				
19	I frequently moved and rotated my panel in order to suit the location of work				
20	It was easy to interact with the game from any position around the table				
21	In general, it was easier to work alone on the table without somebody else next to me				

Finally, could you please write down any further comments, positives, and negatives that you would like the researcher to know about your experience in this study:

Thank you very much

Math Race on Multi-Touch Surfaces (DIS-COL)

Questionnaire: ***Distributed***

All given information is strictly confidential

Name:

Date:

Please tick [✔] the appropriate column that indicate your agreement level with the following statements:

	Statement	Strongly Agree	Agree	Disagree	Strongly Disagree
1	I enjoyed the game experience				
2	It was easy to learn how to play the game				
3	I have played group/network computer games before				
4	The information provided prior the game was clear and easy to understand				
5	In general, I like games that require mathematics skills				
6	I participated in solving the given mathematical problems				
7	The timing of the problems was challenging				
8	I found it easy to get involved in the activity				
9	The game encourages working together like a team				
10	I frequently offered help to my team-mate				
11	I frequently asked for help from my team-mate				
12	I like working in a team				
13	I found the game easy to play without helping each other as a team				
14	I was aware of my team-mate work and progress				
15	I frequently used the provided messaging buttons to communicate with my team-mate				
16	I would like to have text chatting feature with my team-mate				

	Statement	Strongly Agree	Agree	Disagree	Strongly Disagree
17	I would like to have voice communication feature with my team-mate				
18	I have used a multi-touch device before				
19	I quickly understood how to interact with the interface				
20	The displayed information was easy to read				
21	The organization of information on the display surface was clear				
22	Connecting links to panels by dragging lines was easy to do				
23	I frequently moved and rotated my panel in order to suit the location of work				
24	It was easy to interact with the game from any position around the table				
25	I know my team-mate prior to this experiment	YES		NO	

Age: ☐ ***Sex***: Female ☐ Male ☐

Education Level: High School ☐ College ☐ Postgraduate Degree ☐

Finally, could you please write down any further comments, positives, and negatives that you would like the researcher to know about your experience in this study:

Thank you very much

Math Race on Multi-Touch Surfaces (DIS-COL)

Questionnaire: ***Co-Located***

All given information is strictly confidential

Name:

Date:

Please tick [✔] the appropriate column that indicate your agreement level with the following statements:

	Statement	**Strongly Agree**	**Agree**	**Disagree**	**Strongly Disagree**
1	I enjoyed the game experience in co-located setup more than being alone working with a remote team-mate				
2	I felt comfortable playing the game in co-located setup				
3	The information provided prior to this stage of the game was clear and easy to understand				
4	I participated in solving the given mathematical problems				
5	The timing of the problems was challenging				
6	I found it easy to get involved in the activity				
7	The game encourages working together				
8	I frequently offered help to my team-mate				
9	I frequently asked for help from my team-mate				
10	I enjoy working with a nearby team-mate more than a remote one				
11	I found the game easy to play without the help of my team-mate				
12	I was aware of my team-mate work and progress				
13	I found verbal communication more efficient in communicating with my team-mate				
14	The physical presence of my team-mate affected my performance negatively				
15	I did not like being asked for help from my team-mate				

	Statement	Strongly Agree	Agree	Disagree	Strongly Disagree
16	Overall, I am satisfied with how easy it is to use the multi-touch interface				
17	I frequently moved and rotated my panel in order to suit the location of work				
18	It was easy to interact with the game from any position around the table				
19	In general, it was easier to work alone on the table without somebody else next to me				

Finally, could you please write down any further comments, positives, and negatives that you would like the researcher to know about your experience in this study:

Thank you very much

C System Log Sample

This is a very short sample of an automatically generated system log. The actual logs could exceed 3000 lines.

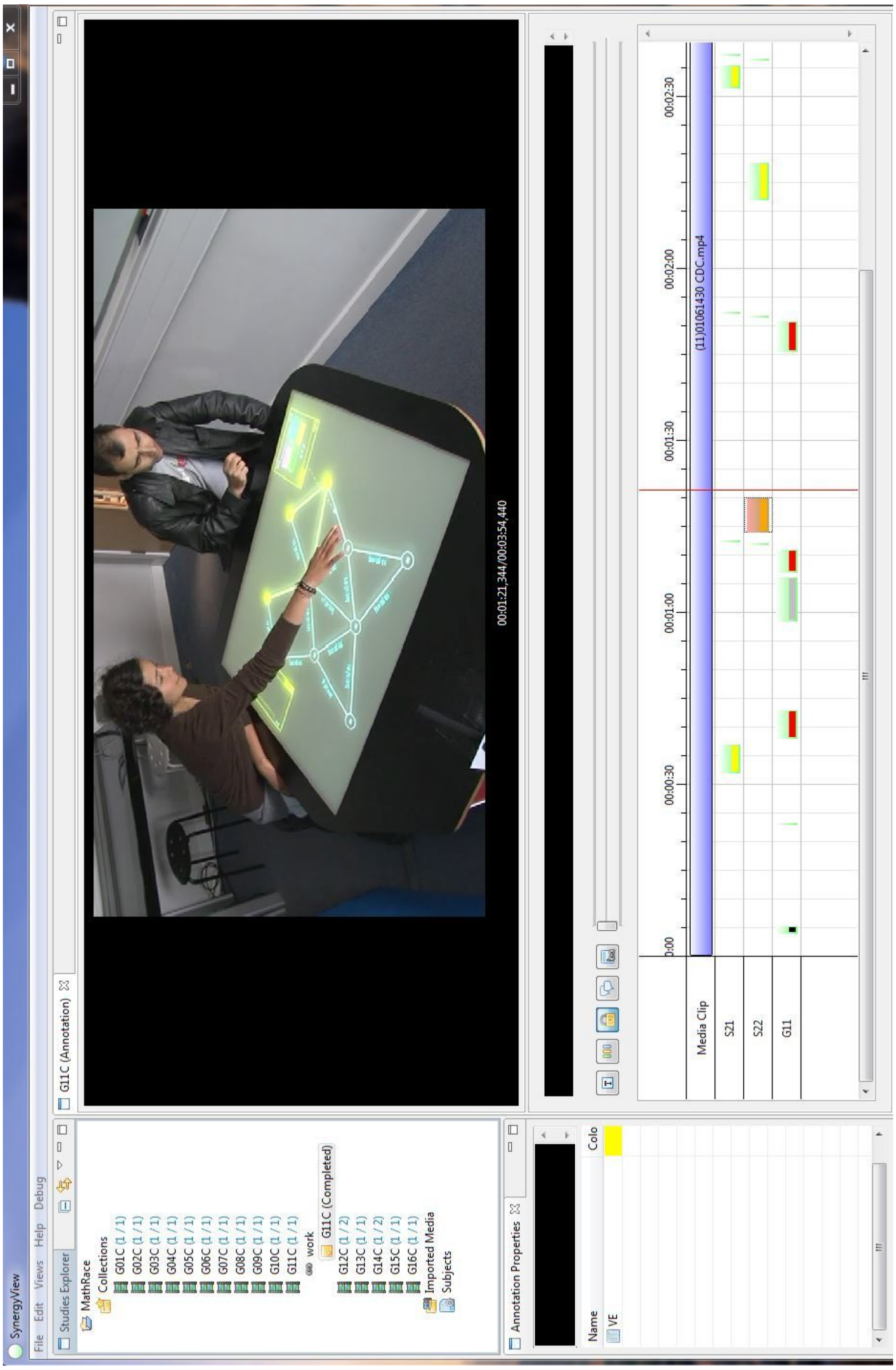
```
[28-05-2012 @ 14:39:52] Open General Log
[14:39:52] Scenario: COOP_COL
[14:39:52] Game Duration: 10 minutes and 0 seconds
[14:39:52] Team 1 members: Katharine, Katy
[14:39:52] START ----------
[14:39:53] A graph of 10 nodes and 17 links has been created
[14:39:53] Main Question Pool: 1000 questions have been generated
[14:41:26] Game has started
[14:41:29] LINK: Attempt to anchor to link (S1, N3)
[14:41:31] LINK: Attempt to anchor link (S1, N3) to Katy's panel of team Team 1
[14:41:31] LINK: link (S1, N3) is anchored to Katy's panel of team Team 1
[14:41:31] LINK: A sub-pool of 40 questions has been generated for link (S1, N3)
[14:41:31] Katy - QB: 1 x 9 => [9] [40] [2] [36] => (1)
[14:41:32] Katy - QB: Answer 1 [9] is clicked. CORRECT
...
[14:41:39] Katy - PANEL TRANSLATE: Panel moved to (133.44, 108.95)
[14:41:40] LINK: Attempt to anchor link (S1, N3) to Katharine's panel of team Team 1
[14:41:40] LINK: link (S1, N3) is anchored to Katharine's panel of team Team 1
[14:41:40] LINK: link (S1, N3) status: ANCHORED2
[14:41:40] LINK: A sub-pool of 40 questions has been generated for link (S1, N3)
[14:41:40] Katharine - QB: 1 x 9 => [9] [40] [2] [36] => (1)
[14:41:41] Katharine - PANEL TRANSLATE: Panel moved to (865.35, 118.80)
...
[14:47:14] NODE: Node N9 has been visited by team Team 1
[14:47:14] NODE: Number of nodes visited by team Team 1 is 10
[14:47:14] LINK: 10 links out of 17 have been solved
[14:47:14] NODE: 10 nodes out of 10 have been visited
[14:47:14] Game has ended in 5 minutes and 43 seconds; with status: MORE_NODES_COVERED
[14:47:14] Links solved: 10/17
[14:47:14] Nodes visited: 10/10
[14:47:34] End ----------

[14:47:34] Close Log
```

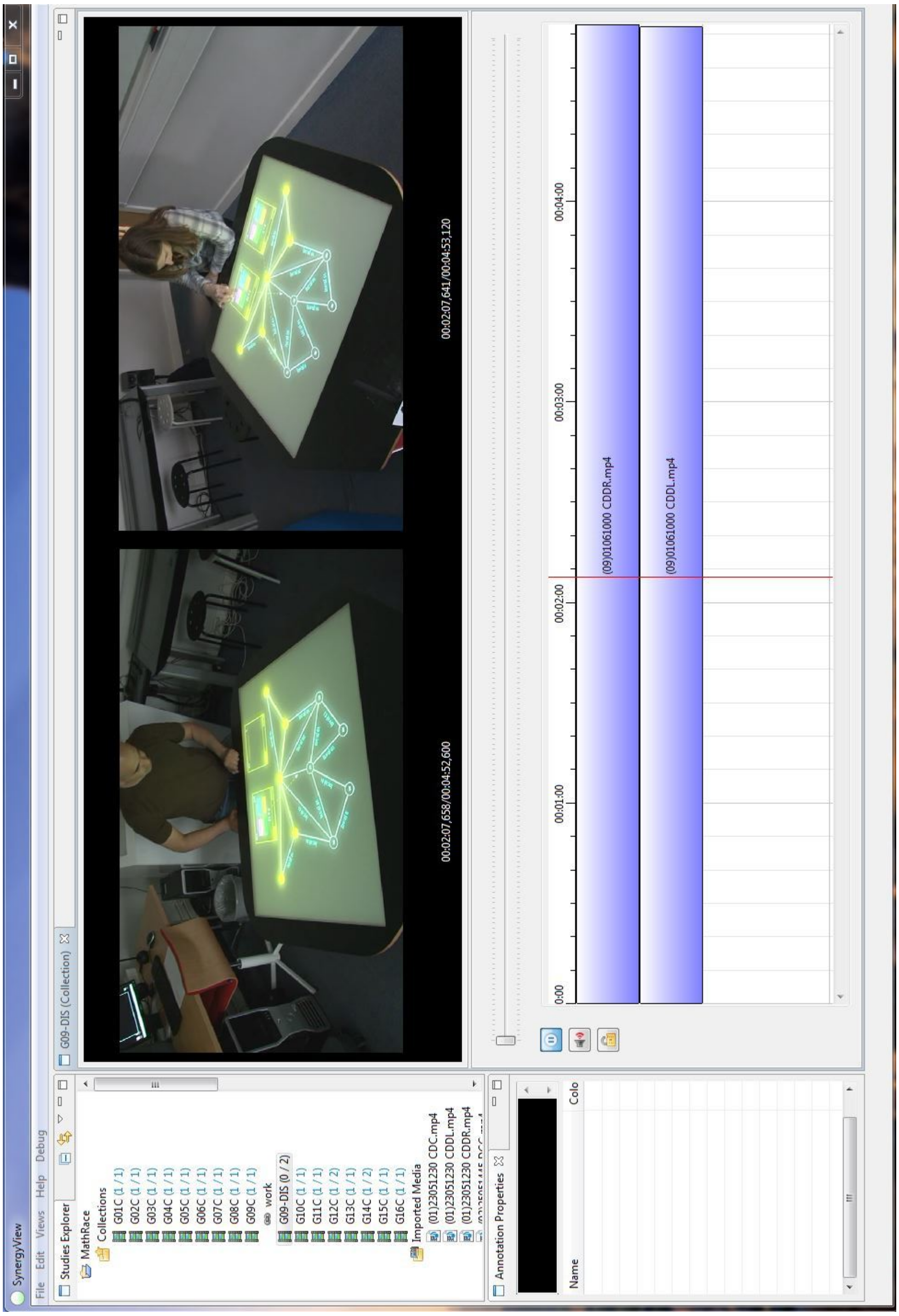
D Video Timeline Sample

SynergyView [4] tool was used in this work for analysing the video recordings that have been made during the experimental sessions. It enables the researcher to add a timeline to the video and tag it with colour-coded attributes and textual annotations. It also has the ability to view two videos next to each other which was used in analysing the distributed scenario videos. Each participant has his/her own timeline of the video, plus a timeline for the group as an entity; so the interactions can be analysed on the individual and team levels. The output of this tool is a sheet of the attributes used in analysis with their frequency count and time span. Samples of the SynergyView tool in use are presented in the following sections.

D.1 Co-Located Video



D.2 Distributed Videos



D.3 Output Sheet

```
G09C - work (G09C)
Time, Duration, Subject, Text
00:00:11 00h:00m:00s:619 G09 + [CommStart]
00:00:13 00h:00m:10s:020 G09 + [DISC]
00:00:23 00h:00m:05s:729 S18 + [VE]
00:00:38 00h:00m:05s:015 S17 + [VE]
00:01:30 00h:00m:04s:108 G09 + [DISC]
00:01:36 00h:00m:17s:385 S17 + [VE]
00:02:06 00h:00m:00s:500 S17 + [CommAskHelp]
00:02:08 00h:00m:00s:500 S18 + [CommAskHelpOK]
00:02:29 00h:00m:03s:510 G09 + [CommOffTopic]
00:02:33 00h:00m:04s:714 G09 + [DISC]
00:02:59 00h:00m:01s:970 S17 + [VE]
00:03:01 00h:00m:14s:422 G09 + [DISC]
00:03:38 00h:00m:04s:564 G09 + [WorkTogetherNoComm]
00:03:43 00h:00m:00s:500 G09 + [CommEnd]
--------------------------------------------
Summary
--------------------------------------------
Subject: S17
Annotation count: 4
Total duration: 00h:00m:24s:870
Attributes Summary
------------------
CommAskHelp: Total - 1 (00h:00m:00s:500)
VE: Total - 3 (00h:00m:24s:370)
--------------------------------------------
Subject: S18 Annotation count: 2
Total duration: 00h:00m:06s:229
Attributes Summary
------------------
CommAskHelpOK: Total - 1 (00h:00m:00s:500)
VE: Total - 1 (00h:00m:05s:729)
--------------------------------------------
Subject: G09
Annotation count: 8
Total duration: 00h:00m:42s:457
Attributes Summary
------------------
CommOffTopic: Total - 1 (00h:00m:03s:510)
CommStart: Total - 1 (00h:00m:00s:619)
CommEnd: Total - 1 (00h:00m:00s:500)
DISC: Total - 4 (00h:00m:33s:264)
WorkTogetherNoComm: Total - 1 (00h:00m:04s:564)

--------------------------------------------
```

E Ethics and Consent Forms

It is required by Durham University that participants in any research experimental work must give their consent by filling and signing forms designed specifically for this purpose. The consent forms that were used in the experiment for this research are on the following pages of this appendix.

Consent Form

Multi-touch Surface Math Race

Date: ________________________

Candidate ID: _________________

Consent Form

Thank you for volunteering to participate in this evaluation of distributed multi-touch collaborative work. You will participate in a short interaction with a multi-touch table surface and will complete some racing games tasks. You will then be asked to fill out a questionnaire about your experience. The experiment will take approximately 40 to 45 minutes and we will be videotaping the sessions for review. The researcher appreciate your candid and direct feedback. All information you give will be kept confidential. Your identity will remain confidential to the extent provided by the law. There are no direct risks to you by participating in this study. The recording of the session will be only reviewed and kept by the researcher. You may withdraw your participation at any time. Thank you.

The participant should complete the whole of this sheet himself/herself

- Have you had an opportunity to ask questions and to discuss the study?

[ ] YES [ ] NO

- Have you received satisfactory answers to all of your questions?

[ ] YES [ ] NO

- Have you received enough information about the study?

[ ] YES [ ] NO

- Who have you spoken to? ***Firas*** *(the researcher)*

- Do you understand that you are free to withdraw from the study at any time and without having to give a reason for withdrawing?

[ ] YES [ ] NO

I have read the procedure described above and I voluntarily agree to participate in this study and have received a copy of this description

Signed ....………................
Date ....…..
(NAME IN BLOCK LETTERS) ....………..............……........

Consent Form

Voluntary Release of Video and Photographs

I grant the researchers (Durham University) permission to use the video and photographs of my participation in the distributed multi-touch collaborative work experiment. The videos and photographs are to be used in scholarly publications. I understand that I am not obligated to complete this part of the consent form and it will in no way impact my participation in the study. I understand that my name and personal information will be kept with strict confidentiality.

Signed ....………................
Date ....…..
(NAME IN BLOCK LETTERS) ....………..............……........

References

[1] ISO 9241: Ergonomics of human-system interaction – part 210: Human-centred design for interactive systems. http://www.iso.org/iso/iso_catalogue/52075.

[2] The "R" project for statistical computing. http://www.r-project.org/.

[3] SynergyNet - platform independent multi-touch software. http://code.google.com/p/synergynet/.

[4] SynergyView - a timeline analysis tool for videos. http://code.google.com/p/synergyview/.

[5] TUIO: tangible user interface objects. http://www.tuio.org/.

[6] Saleema Amershi and Meredith Ringel Morris. CoSearch: a system for co-located collaborative web search. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '08, page 1647–1656, New York, NY, USA, 2008. ACM.

[7] Saleema Amershi and Meredith Ringel Morris. Co-located collaborative web search: understanding status quo practices. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '09, page 3637–3642, New York, NY, USA, 2009. ACM.

[8] Edward Anstead, Abigail Durrant, Steve Benford, and David Kirk. Tabletop games for photo consumption at theme parks. In *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces*, ITS '12, page 61–70, New York, NY, USA, 2012. ACM.

[9] Ronald Baecker, Jonathan Grudin, Bill Buxton, and Saul Greenberg. *Reading in Human-Computer Interaction: Toward the Year 2000.* Morgan Kaufmann Publishers Inc., 2nd edition, 1995.

[10] Aruna D. Balakrishnan, Susan R. Fussell, and Sara Kiesler. Do visualizations improve synchronous remote collaboration? In *Proceedings of the twenty-sixth annual SIGCHI conference on Human factors in computing systems*, CHI '08, page 1227–1236, New York, NY, USA, 2008. ACM.

[11] Aruna D. Balakrishnan, Susan R. Fussell, Sara Kiesler, and Aniket Kittur. Pitfalls of information access with visualizations in remote collaborative analysis. In *Proceedings of the 2010 ACM conference on Computer supported cooperative work*, CSCW '10, page 411–420, New York, NY, USA, 2010. ACM.

[12] Phil Barnard and Jon May. Interactions with advanced graphical interfaces and the deployment of latent human knowledge. In Fabio Paternó, editor, *Interactive Systems: Design, Specification, and Verification*, Focus on Computer Graphics, pages 15–49. Springer Berlin Heidelberg, 1995.

[13] Mohammad Basheri and Liz Burd. Exploring the significance of multi-touch tables in enhancing collaborative software design using UML. In *In proceeding of: 42nd ASEE/IEEE Frontiers in Education Conference*, pages 735 –739, Seattle, Washington, USA, 2012.

[14] Mohammed Basheri, Liz Burd, and Nilufar Baghaei. A multi-touch interface for enhancing collaborative UML diagramming. In *Proceedings of the 24th Australian Computer-Human Interaction Conference*, OzCHI '12, page 30–33. ACM, 2012.

[15] M. Beaudouin-Lafon. Instrumental interaction: an interaction model for designing post-WIMP user interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, page 446–453, 2000.

[16] M. Beaudouin-Lafon. Designing interaction, not interfaces. In *Proceedings of the 2003 ACM SIGMOD international conference on Management of data*, page 668–668, 2004.

[17] Elham Beheshti, Anne Van Devender, and Michael Horn. Touch, click, navigate: comparing tabletop and desktop interaction for map navigation tasks. In *Proceedings*

of the 2012 ACM international conference on Interactive tabletops and surfaces, ITS '12, page 205–214, New York, NY, USA, 2012. ACM.

[18] Mathilde Bekker, Wolmet Barendregt, Silvia Crombeen, and Mariëlle Biesheuvel. Evaluating usability and challenge during initial and extended use of children's computer games. In *People and Computers XVIII — Design for Life*, pages 331–345. Springer London, 2005.

[19] Guillaume Besacier, Gaétan Rey, Marianne Najm, Stéphanie Buisine, and Frédéric Vernier. Paper metaphor for tabletop interaction design. In Julie A. Jacko, editor, *Human-Computer Interaction. Interaction Platforms and Techniques*, number 4551 in Lecture Notes in Computer Science, pages 758–767. Springer Berlin Heidelberg, 2007.

[20] J. Biström, A. Cogliati, and K. Rouhiainen. Post-wimp user interface model for 3d web applications. In *Research Seminar on Digital Media*, Helsinki, Finland, 2005. Helsinki University of Technology Telecommunications Software and Multimedia Laboratory.

[21] Michael E. Bratman. Shared cooperative activity. *The Philosophical Review*, 101(2):327, 1992.

[22] Scott Brave, Hiroshi Ishii, and Andrew Dahley. Tangible interfaces for remote collaboration and communication. In *Proceedings of the 1998 ACM conference on Computer supported cooperative work - CSCW '98*, pages 169–178, 1998.

[23] Bill Buxton and B. Myers. A study in two-handed input. http://www.billbuxton.com/2hands.html, 1986.

[24] John Carroll. The encyclopedia of human-computer interaction, 2nd ed. http://www.interaction-design.org/encyclopedia/hci, 2013.

[25] John M. Carroll, editor. *HCI Models, Theories, and Frameworks: Toward a Multidisciplinary Science.* Morgan Kaufmann, 2003.

[26] Jacob Cohen, Patricia Cohen, Stephen G. West, and Leona S. Aiken. *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences.* Routledge Academic, 3 edition, 2002.

[27] Anthony Collins. Enabling collaborative tabletop file system interaction through similarity-based browsing. http://www.acm.org/src/Collins/collins-acmsrc/collins.html, 2008.

[28] Inc Apple Computer. *Apple Human Interface Guidelines: The Apple Desktop Interface*. Addison-Wesley (C), 1987.

[29] Mihaly Csikszentmihalyi. *Flow: The Psychology of Optimal Experience*. Harper Perennial Modern Classics, 1st edition, 2008.

[30] John V. Dempsey, Linda L. Haynes, Barbara A. Lucassen, and Maryann S. Casey. Forty simple computer games and what they could mean to educators. *Simul. Gaming*, 33(2):157–168, 2002.

[31] P. Dietz and D. Leigh. DiamondTouch: a multi-user touch technology. In *Proceedings of the 14th annual ACM symposium on User interface software and technology*, page 219–226, 2001.

[32] Alan Dix, Janet Finlay, Gregory D. Abowd, and Russell Beale. *Human Computer Interaction*. Prentice Hall, 3 edition, 2003.

[33] Paul Dourish and Victoria Bellotti. Awareness and coordination in shared workspaces. In *Proceedings of the 1992 ACM conference on Computer-supported cooperative work*, CSCW '92, page 107–114, New York, NY, USA, 1992. ACM.

[34] Jeff Dyck, David Pinelle, Barry Brown, and Carl Gutwin. Learning from games: HCI design innovations in entertainment software. In *Proc. Graphics Interface 2003*, pages 237–246, Halifax, Canada, 2003.

[35] Ray E. Eberts. *User Interface Design*. Prentice-Hall, international edition edition, 1993.

[36] Jörg Edelmann, Philipp Mock, Andreas Schilling, Peter Gerjets, Wolfgang Rosenstiel, and Wolfgang Straßer. Towards the keyboard of oz: learning individual soft-keyboard models from raw optical sensor data. In *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces*, ITS '12, page 163–172, New York, NY, USA, 2012. ACM.

[37] Thomas D. Erickson. Working with interface metaphors. In *Human-computer interaction: toward the year 2000*, pages 147–151. Morgan Kaufmann Publishers Inc., 1995.

[38] Deniz Eseryel, Radha Ganesan, and Gerald S. Edmonds. Review of computer-supported collaborative work systems. *Educational Technology & Society*, 5(2):2002, 2002.

[39] Jinjuan Feng, Clare-Marie Karat, and Andrew Sears. How productivity improves in hands-free continuous dictation tasks: lessons learned from a longitudinal study. *Interacting with Computers*, 17(3):265–289, 2005.

[40] Jinjuan Feng, Andrew Sears, and Clare-Marie Karat. A longitudinal evaluation of hands-free speech-based navigation during dictation. *International Journal of Human-Computer Studies*, 64(6):553–569, 2006.

[41] Andy Field. *Discovering Statistics Using SPSS*. Sage Publications Ltd, third edition edition, 2009.

[42] Andy Field and Dr Graham J. Hole. *How to Design and Report Experiments*. Sage Publications Ltd, 2003.

[43] C. Forlines, D. Wigdor, C. Shen, and R. Balakrishnan. Direct-touch vs. mouse input for tabletop displays. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, page 647–656, 2007.

[44] John Fox. *Applied Regression Analysis and Generalized Linear Models*. SAGE Publications, Inc, second edition edition, 2008.

[45] Rosemary Garris, Robert Ahlers, and James E. Driskell. Games, motivation, and learning: A research and practice model. *Simulation & Gaming*, 33(4):441–467, 2002.

[46] Wooi-Boon Goh, Wei Shou, Jacquelyn Tan, and G.T. Jackson Lum. Interaction design patterns for multi-touch tabletop collaborative games. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '12, page 141–150, New York, NY, USA, 2012. ACM.

[47] M. Green and R. Jacob. Software architectures and metaphors for non-wimp user interfaces. *Computer Graphics*, 25(3):229–235, 1991.

[48] Frank E. Grubbs. Procedures for detecting outlying observations in samples. *Technometrics*, 11(1):1–21, 1969.

[49] Y Guiard. Asymmetric division of labor in human skilled bimanual action: the kinematic chain as a model. *Journal of motor behavior*, 19(4):486–517, 1987.

[50] C. Gutwin and S. Greenberg. The mechanics of collaboration: developing low cost usability evaluation methods for shared workspaces. In *IEEE 9th International Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises, 2000. (WET ICE 2000). Proeedings*, pages 98–103. IEEE, 2000.

[51] Carl Gutwin and Saul Greenberg. Design for individuals, design for groups: tradeoffs between power and workspace awareness. In *Proceedings of the 1998 ACM conference on Computer supported cooperative work*, CSCW '98, page 207–216, New York, NY, USA, 1998. ACM.

[52] Carl Gutwin and Saul Greenberg. A descriptive framework of workspace awareness for real-time groupware. *Comput. Supported Coop. Work*, 11(3):411–446, 2002.

[53] Vicki Ha, Kori M. Inkpen, Tara Whalen, and Regan L. Mandryk. Direct intentions: The effects of input devices on collaboration around a tabletop display. In *Proceedings of the First IEEE International Workshop on Horizontal Interactive Human-Computer Systems*, TABLETOP '06, page 177–184, Washington, DC, USA, 2006. IEEE Computer Society.

[54] Jefferson Y Han. Low-cost multi-touch sensing through frustrated total internal reflection. In *Proceedings of the 18th annual ACM symposium on User interface software and technology*, UIST '05, page 115–118, Seattle, WA, USA, 2005. ACM.

[55] Jefferson Y. Han. Multi-touch interaction wall. In *ACM SIGGRAPH 2006 Emerging technologies*, SIGGRAPH '06, New York, NY, USA, 2006. ACM.

[56] Amanda Harris, Jochen Rick, Victoria Bonnett, Nicola Yuill, Rowanne Fleck, Paul Marshall, and Yvonne Rogers. Around the table: are multiple-touch surfaces better than single-touch for children's collaborative interactions? In *Proceedings of the*

9th international conference on Computer supported collaborative learning - Volume 1, CSCL'09, page 335–344. International Society of the Learning Sciences, 2009.

[57] Andrew Hatch, Steve Higgins, and Emma Mercier. SynergyNet: supporting collaborative learning in an immersive environment. In *STELLAR Workshop 2009: "Tabletops for Education and Training"*, Garmisch-Partenkirchen, Germany, 2009.

[58] Hewett, Baecker, Card, Carey, and Gasen. ACM SIGCHI: definition and overview of human-computer interaction. http://old.sigchi.org/cdg/cdg2.html, 2009.

[59] Thomas Hill and Paul Lewicki. *Statistics: Methods and Applications*. StatSoft, Inc., 2005.

[60] Otmar Hilliges, Lucia Terrenghi, Sebastian Boring, David Kim, Hendrik Richter, and Andreas Butz. Designing for collaborative creative problem solving. In *Proceedings of the 6th ACM SIGCHI conference on Creativity & cognition*, C&C '07, page 137–146, New York, NY, USA, 2007. ACM.

[61] K. Hinckley, M. Czerwinski, and M. Sinclair. Interaction and modeling techniques for desktop two-handed input. In *Proceedings of the 11th annual ACM symposium on User interface software and technology*, page 49–58, 1998.

[62] Edwin Hutchins. The technology of team navigation. In *Intellectual teamwork*, pages 191–220. L. Erlbaum Associates Inc., Hillsdale, NJ, USA, 1990.

[63] Petra Isenberg and Sheelagh Carpendale. Interactive tree comparison for co-located collaborative information visualization. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1232–1239, 2007.

[64] Petra Isenberg, Danyel Fisher, Sharoda A. Paul, Meredith Ringel Morris, Kori Inkpen, and Mary Czerwinski. An exploratory study of co-located collaborative visual analytics around a tabletop display. *IEEE Transactions on Visualization and Computer Graphics*, 18(5):689–702, 2012.

[65] H. Ishii and M. Kobayashi. ClearBoard: a seamless medium for shared drawing and conversation with eye contact. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, page 525–532, 1992.

[66] Robert J.K. Jacob, Audrey Girouard, Leanne M. Hirshfield, Michael S. Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. Reality-based interaction: a framework for post-WIMP interfaces. In *Proceeding of the twenty-sixth annual SIGCHI conference on Human factors in computing systems*, pages 201–210, Florence, Italy, 2008. ACM.

[67] Susan Jamieson. Likert scales: how to (ab)use them. *Medical education*, 38(12):1217–1218, 2004.

[68] B. J Jansen. The graphical user interface. *ACM SIGCHI Bulletin*, 30(2):22–26, 1998.

[69] Anker Helms Jørgensen. Marrying HCI/Usability and computer games: a preliminary look. In *Proceedings of the third Nordic conference on Human-computer interaction*, NordiCHI '04, page 393–396, New York, NY, USA, 2004. ACM.

[70] Alan Kay. User interface: A personal view. In *The Art of Human-Computer Interface Design*, page 121–131. Addison-Wesley Longman Publishing Co., Inc., 1990.

[71] A. S Kharrufa. *Digital tabletops and collaborative learning.* PhD, Newcastle University, Newcastle, UK, 2010.

[72] Ahmed Kharrufa, Patrick Olivier, and Philip Heslop. TangiSoft: a tangible direct-touch tabletop keyboard. In *World Conference on Educational Multimedia, Hypermedia and Telecommunications 2009*, pages 918–926, 2009.

[73] Kenrick Kin, Maneesh Agrawala, and Tony DeRose. Determining the benefits of direct-touch, bimanual, and multifinger input on a multitouch workstation. In *Proceedings of Graphics Interface 2009*, page 1–6, 2009.

[74] Russell Kruger, Sheelagh Carpendale, Stacey D. Scott, and Saul Greenberg. Roles of orientation in tabletop collaboration: Comprehension, coordination and communication. *Comput. Supported Coop. Work*, 13(5-6):501–537, 2004.

[75] Russell Kruger, Sheelagh Carpendale, Stacey D. Scott, and Anthony Tang. Fluid integration of rotation and translation. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 601–610, Portland, Oregon, USA,

2005. ACM.

[76] Thomas K. Landauer. Let's get real: a position paper on the role of cognitive psychology in the design of humanly useful and usable systems. In *Designing interaction: psychology at the human-computer interface*, pages 60–73. Cambridge University Press, 1991.

[77] Jean Lave. *Cognition in Practice: Mind, Mathematics and Culture in Everyday Life*. Cambridge University Press, 1988.

[78] Jonathan Lazar, Jinjuan Heidi Feng, and Harry Hochheiser. *Research Methods in Human-computer Interaction*. John Wiley & Sons, 2009.

[79] Robert M. Liebert and Lynn Langenbach Liebert. *Science and Behavior: An Introduction to Methods of Psychological Research*. Prentice Hall College Div, 4 sub edition, 1994.

[80] Johannes Luderschmidt. Throng – a cross-platform multiplexer for tuio messages and packets. http://jetpack.wordpress.com/jetpack-comment/, 2011.

[81] Tony Manninen. Towards communicative, collaborative and constructive multi-player games. In *Computer Games and Digital Cultures Conference*, pages 155–169, Tampere, Finland, 2002. University of Tampere.

[82] James A. McNaughton. *Adapting Multi-touch Systems to Capitalise on Different Display Shapes*. Master's thesis, Durham University, Durham, UK, 2011.

[83] Microsoft. Microsoft PixelSense. http://www.microsoft.com/en-us/pixelsense/, 2013.

[84] Microsoft.com Operations. The GUI versus the command line. http://blogs.technet.com/mscom/archive/2007/03/12/the-gui-vs-comm.aspx, 2007.

[85] L G Militello and R J Hutton. Applied cognitive task analysis (ACTA): a practitioner's toolkit for understanding cognitive task demands. *Ergonomics*, 41(11):1618–1641, 1998.

[86] Max Möllers, Patrick Zimmer, and Jan Borchers. Direct manipulation and the third dimension: co-planar dragging on 3d displays. In *Proceedings of the 2012*

ACM international conference on Interactive tabletops and surfaces, ITS '12, page 11–20, New York, NY, USA, 2012. ACM.

[87] M. Morris. A survey of collaborative web search practices. In *Proceeding of the twenty-sixth annual SIGCHI conference on Human factors in computing systems*, pages 1657–1660, Florence, Italy, 2008. ACM.

[88] M. R Morris and T. Winograd. Quantifying collaboration on computationally-enhanced tables. In *CSCW 2004 Workshop on Methodologies for Evaluating Collaboration Behaviour in Co-located Environments*, 2004.

[89] Meredith Morris. *Supporting Effective Interaction with Tabletop Groupware*. PhD thesis, Stanford University, 2006.

[90] Meredith Ringel Morris and Eric Horvitz. SearchTogether: an interface for collaborative web search. In *Proceedings of the 20th annual ACM symposium on User interface software and technology*, UIST '07, page 3–12, New York, NY, USA, 2007. ACM.

[91] Meredith Ringel Morris, Jarrod Lombardo, and Daniel Wigdor. WeSearch: supporting collaborative search and sensemaking on a tabletop display. In *Proceedings of the 2010 ACM conference on Computer supported cooperative work*, pages 401–410, Savannah, Georgia, USA, 2010. ACM.

[92] Meredith Ringel Morris, Dan Morris, and Terry Winograd. Individual audio channels with single display groupware: Effects on communication and task strategy. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, page 578–581, 2004.

[93] Meredith Ringel Morris and Frederic Vernier. Beyond "Social protocols": Multi-user coordination policies for co-located groupware. *ACM*, 6(3):262–265, 2004.

[94] Christian Müller-Tomfelde, editor. *Tabletops - Horizontal Interactive Displays*. Springer, 2010 edition, 2010.

[95] Christian Müller-Tomfelde and Morten Fjeld. A short history of tabletop research, technologies, and products. In *Tabletops - Horizontal Interactive Displays*, Human-Computer Interaction Series, pages 1–24. Springer London, 2010.

[96] Brad A. Myers. A brief history of human-computer interaction technology. *interactions*, 5(2):44–54, 1998.

[97] Brad A. Myers, Rishi Bhatnagar, Jeffrey Nichols, Choon Hong Peck, Dave Kong, Robert Miller, and A. Chris Long. Interacting at a distance: measuring the performance of laser pointers and other devices. In *Proceedings of the SIGCHI conference on Human factors in computing systems: Changing our world, changing ourselves*, pages 33–40, Minneapolis, Minnesota, USA, 2002. ACM.

[98] Miguel A. Nacenta, Dzmitry Aliakseyeu, Sriram Subramanian, and Carl Gutwin. A comparison of techniques for multi-display reaching. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '05, page 371–380, New York, NY, USA, 2005. ACM.

[99] Miguel A. Nacenta, David Pinelle, Dane Stuckel, and Carl Gutwin. The effects of interaction technique on coordination in tabletop groupware. In *Proceedings of Graphics Interface 2007*, GI '07, page 191–198, New York, NY, USA, 2007. ACM.

[100] Diana G. Oblinger. The next generation of educational engagement. *Journal of Interactive Media in Education*, 8(1):1–18, 2004.

[101] Gary M. Olson and Judith S. Olson. Distance matters. *Hum.-Comput. Interact.*, 15(2):139–178, 2000.

[102] Gary M. Olson and Judith S. Olson. Groupware and computer-supported cooperative work. In *The human-computer interaction handbook: fundamentals, evolving technologies and emerging applications*, pages 583–595. L. Erlbaum Associates Inc., 2003.

[103] Judith S. Olson, Lisa Covi, Elena Rocco, William J. Miller, and Paul Allie. A room of your own: what would it take to help remote groups work as well as collocated groups? In *CHI 98 Cconference Summary on Human Factors in Computing Systems*, CHI '98, page 279–280, New York, NY, USA, 1998. ACM.

[104] Judith S. Olson and Stephanie Teasley. Groupware in the wild: lessons learned from a year of virtual collocation. In *Proceedings of the 1996 ACM conference on Computer supported cooperative work*, CSCW '96, page 419–427, New York, NY, USA, 1996. ACM.

[105] Wanda J. Orlikowski. Learning from notes: organizational issues in groupware implementation. In *Proceedings of the 1992 ACM conference on Computer-supported cooperative work*, pages 362–369, Toronto, Ontario, Canada, 1992. ACM.

[106] Sharoda A. Paul and Meredith Ringel Morris. CoSense: enhancing sensemaking for collaborative web search. In *Proceedings of the 27th international conference on Human factors in computing systems*, CHI '09, page 1771–1780, New York, NY, USA, 2009. ACM.

[107] Jenny Preece, Yvonne Rogers, and Helen Sharp. *Interaction Design: Beyond Human-Computer Interaction*. John Wiley & Sons, 2002.

[108] Marc Prensky. *Digital Game-Based Learning*. Paragon House, 1 edition, 2007.

[109] Bruce A. Reinig. Toward an understanding of satisfaction with the process and outcomes of teamwork. *Journal of Management Information Systems*, 19(4):65–83, 2003.

[110] Thomas Richardson, Liz Burd, and Shamus Smith. Guidelines for supporting real-time multi-touch applications. *Software: Practice and Experience*, 43(3):1–19, 2013.

[111] John J. Rodwell, René Kienzle, and Mark A. Shadur. The relationship among work-related perceptions, employee attitudes, and employee performance: The integral role of communications. *Human Resource Management*, 37(3-4):277–293, 1998.

[112] Y Rogers and S Lindley. Collaborating around vertical and horizontal large interactive displays: which way is best? *Interacting with Computers*, 16(6):1152, 1133, 2004.

[113] Yvonne Rogers, Youn-kyung Lim, William Hazlewood, and Paul Marshall. Equal opportunities: Do shareable interfaces promote more group participation than single user displays? *Human-Computer Interaction*, 24(1):79–116, 2009.

[114] Robert Rosenthal and Ralph L. Rosnow. *Essentials of Behavioral Research: Methods and Data Analysis*. McGraw-Hill Higher Education, 3 edition, 2007.

[115] Steven M Ross and Gary R Morrison. *Getting started in instructional technology research*. Association for Educational Communications & Technology, Bloomington, Ind., 4 edition, 2007.

[116] K. Ryall, C. Forlines, C. Shen, and M. R Morris. Exploring the effects of group size and table size on interactions with tabletop shared-display groupware. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, page 284–293, 2004.

[117] D. Saffer. *The role of metaphor in interaction design*. PhD thesis, Carnegie Mellon University, Pittsburgh, Pennsylvania, United States, 2005.

[118] Stacey D. Scott, Karen D. Grant, and Regan L. Mandryk. System guidelines for co-located, collaborative work on a tabletop display. In *Proceedings of the eighth conference on European Conference on Computer Supported Cooperative Work*, ECSCW'03, page 159–178, Norwell, MA, USA, 2003. Kluwer Academic Publishers.

[119] Stacey D. Scott, M. Sheelagh, T. Carpendale, and Kori M. Inkpen. Territoriality in collaborative tabletop workspaces. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, CSCW '04, page 294–303, New York, NY, USA, 2004. ACM.

[120] C. Shen, N. Lesh, B. Moghaddam, P. Beardsley, and R. S Bardsley. Personal digital historian: user interface design. In *Conference on Human Factors in Computing Systems*, page 29–30, 2001.

[121] C. Shen, N. Lesh, and F. Vernier. Personal digital historian: Story sharing around the table. *interactions*, 10(2):15–22, 2003.

[122] C. Shen, F. D Vernier, C. Forlines, and M. Ringel. DiamondSpin: an extensible toolkit for around-the-table interaction. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, page 167–174, 2004.

[123] Chia Shen. Interactive tabletops. In *SIGGRAPH 2007*, pages 36–49, San Diego, California, USA, 2007.

[124] Chia Shen, Neal B. Lesh, Frederic Vernier, Clifton Forlines, and Jeana Frost. Sharing and building digital group histories. In *Proceedings of the 2002 ACM*

conference on Computer supported cooperative work, pages 324–333, New Orleans, Louisiana, USA, 2002. ACM.

[125] Chia Shen, Kathy Ryall, Clifton Forlines, Alan Esenther, Frederic D. Vernier, Katherine Everitt, Mike Wu, Daniel Wigdor, Meredith Ringel Morris, Mark Hancock, and Edward Tse. Informing the design of direct-touch tabletops. *IEEE Comput. Graph. Appl.*, 26(5):36–46, 2006.

[126] B. Shneiderman. Direct manipulation: A step beyond programming languages. In R. M. Baecker and W. A. S. Buxton, editors, *Human-computer interaction*, page 461–467. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1987.

[127] Ben Shneiderman. Touch screens now offer compelling uses. *IEEE Softw.*, 8(2):93–94, 107, 1991.

[128] Ben Shneiderman. *Designing the User Interface, 3rd Ed.* Addison Wesley, 3 edition, 1997.

[129] Ben Shneiderman. Why not make interfaces better than 3D reality? *IEEE Comput. Graph. Appl.*, 23(6):12–15, 2003.

[130] Norbert A. Streitz, Jörg Geißler, Torsten Holmer, Shin'ichi Konomi, Christian Müller-Tomfelde, Wolfgang Reischl, Petra Rexroth, Peter Seitz, and Ralf Steinmetz. i-LAND: an interactive landscape for creativity and innovation. In *Proceedings of the SIGCHI conference on Human factors in computing systems: the CHI is the limit*, pages 120–127, Pittsburgh, Pennsylvania, United States, 1999. ACM.

[131] Ivan E. Sutherland. Sketch pad a man-machine graphical communication system. In *Proceedings of the SHARE design automation workshop*, pages 6.329–6.346. ACM, 1964.

[132] Anthony Tang, Michael Boyle, and Saul Greenberg. Understanding and mitigating display and presence disparity in mixed presence groupware. *Journal of Research and Practice in Information Technology*, 37(2):193–210, 2005.

[133] Anthony Tang, Carman Neustaedter, and Saul Greenberg. VideoArms: embodiments for mixed presence groupware. In Nick Bryan-Kinns, Ann Blanford, Paul Curzon, and Laurence Nigay, editors, *People and Computers XX — Engage*,

pages 85–102. Springer London, London, 2007.

[134] Anthony Tang, Melanie Tory, Barry Po, Petra Neumann, and Sheelagh Carpendale. Collaborative coupling over tabletop displays. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*, CHI '06, page 1181–1190, New York, NY, USA, 2006. ACM.

[135] J. C Tang and S. Minneman. VideoWhiteboard: video shadows to support remote collaboration. In *Proceedings of the SIGCHI conference on Human factors in computing systems: Reaching through technology*, pages 315–322, 1991.

[136] John C. Tang. Findings from observational studies of collaborative work. *Int. J. Man-Mach. Stud.*, 34(2):143–160, 1991.

[137] Ashley George Taylor. WIMP interfaces. Technical report, College of Computing, Georgia Institute of Technology, Georgia, USA, 1997.

[138] Dov Te'eni, Jane M. Carey, and Ping Zhang. *Human-Computer Interaction: Developing Effective Organizational Information Systems.* John Wiley & Sons, 2006.

[139] Henry C. Thode. *Testing For Normality.* CRC Press, 2002.

[140] P. Tuddenham and P. Robinson. Distributed tabletops: Supporting remote and mixed-presence tabletop collaboration. In *Second Annual IEEE International Workshop on Horizontal Interactive Human-Computer Systems, 2007. TABLETOP '07*, pages 19 –26, 2007.

[141] Philip Tuddenham, Ian Davies, and Peter Robinson. WebSurface: an interface for co-located collaborative information gathering. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, ITS '09, page 181–188, New York, NY, USA, 2009. ACM.

[142] Michael B. Twidale, David M. Nichols, and Chris D. Paice. Browsing is a collaborative process. *Inf. Process. Manage.*, 33(6):761–783, 1997.

[143] A. Van Dam. Post-WIMP user interfaces. *COMMUNICATIONS OF THE ACM*, 40(2):63–67, 1997.

[144] Gerrit C. van der Veer. Cognitive ergonomics in interface design - discussion of a moving science. *Journal of Universal Computer Science*, 14(16):2614–2629, 2008.

[145] J.R. Wallace and S.D. Scott. Contextual design considerations for co-located, collaborative tables. In *3rd IEEE International Workshop on Horizontal Interactive Human Computer Systems, 2008. TABLETOP 2008*, pages 57–64, 2008.

[146] Noreen M. Webb and Sydney Farivar. Promoting helping behavior in cooperative small groups in middle school mathematics. *American Educational Research Journal*, 31(2):369–395, 1994.

[147] Noreen M. Webb and Ann M. Mastergeorge. The development of students' helping behavior and learning in peer-directed small groups. *Cognition and Instruction*, 21(4):361–428, 2003.

[148] Noreen M. Webb, Jonathan D. Troper, and Randy Fall. Constructive activity and learning in collaborative small groups. *Journal of Educational Psychology*, 87(3):406–423, 1995.

[149] Pierre Wellner. Interacting with paper on the DigitalDesk. *Commun. ACM*, 36(7):87–96, 1993.

[150] Wayne Westerman, John G. Elias, and Alan Hedge. Multi-touch: A new tactile 2-d gesture interface for human-computer interaction. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 45(6):632–636, 2001.

[151] D. Wigdor, J. Fletcher, and G. Morrison. Designing user interfaces for multi-touch and gesture devices. In *Proceedings of the 27th international conference extended abstracts on Human factors in computing systems*, page 2755–2758, 2009.

[152] D. Wigdor, G. Perm, K. Ryall, A. Esenther, and C. Shen. Living with a tabletop: Analysis and observations of long term office use of a multi-touch table. In *Horizontal Interactive Human-Computer Systems, 2007. TABLETOP'07. Second Annual IEEE International Workshop on*, page 60–67, 2007.

[153] Paul Wilson. *Computer Supported Cooperative Work: An Introduction.* Springer, 1991.

[154] P M Wortman. Evaluation research: A methodological perspective. *Annual Review of Psychology*, 34(1):223–260, 1983.

[155] Peter Wright, Bob Fields, and Michael Harrison. Analysing human-computer interaction as distributed cognition: The resources model. *Human Computer Interaction*, 15:1–42, 1999.

[156] Muna Yousef. Assessment of metaphor efficacy in user interfaces for the elderly: A tentative model for enhancing accessibility. *ACM SIGARCH Computer Architecture News*, 28(2):83–94, 2001.

[157] Muna Yousef. The role of metaphor in UI design for UA. In *Proceedings of the 2001 EC/NSF workshop on Universal accessibility of ubiquitous computing: providing for the elderly*, page 124, 2001.